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ON THE TEMPERATURE, SECULAR COOLING AND CONTRACTION OF THE EARTH, AND ON THE THEORY OF EARTHQUAKES HELD BY THE ANCIENTS.

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I. ON THE TEMPERATURE AND INTERNAL STATE OF THE EARTH.

§ 1. *General Considerations.*

It is well known that Fourier devoted almost the whole of his life to those famous mathematical investigations by which he established the laws for the propagation of heat in solid bodies. His first memoir was communicated to the Institut de France in 1807, but with several subsequent memoirs was allowed to rest in the Archives till 1822, when all were at length published in the celebrated "Théorie Analytique de la Chaleur." Prior to this, however, in the *Bulletin des Sciences par la Société Philomathique de Paris,* avril, 1820, pp. 58–70, there appeared an "Extrait d'un Mémoire sur le Refroidissement séculaire du Globe Terrestre," which contains the earliest detailed statement of the secular cooling of the earth (cf. "Oeuvres de Fourier," edited by Darboux, Tome II., pp. 271–288).

In 1827 Fourier submitted to the Academy of Sciences an additional memoir on the "Temperatures of the Terrestrial Globe and of the Planetary Spaces" (cf. "Oeuvres de Fourier," Tome II., p. 97). He justly remarks that the question of terrestrial temperature is one of the most important and one of the most difficult in the whole range of natural philosophy. This view is still held by physicists to-day, and therefore any inquiry which will materially advance our knowledge of the subject may be welcome to the investigator of the physical problems of our globe. Some of the results here obtained are only approximate; yet they appear to fix fairly accurate limits to the effects which may be ascribed to the movement of heat within the earth, and accordingly may not be wholly without interest to those who are occupied with this difficult subject.

The theory that our earth is undergoing secular cooling, and therefore contracting, is widely spread in the literature of contemporary science; in fact it is made the basis of nearly all current speculations in geology, geophysics, seismology and the related branches of natural philosophy. A theory so widely spread in modern thought and so long current would naturally have great presumptive evidence of truth, and therefore should not be lightly set aside. Yet it often happens that later researches supply criteria which were not available to the earlier investigators; and subsequent workers are required to take account of these advances. This appears to be the situation at the present time in respect to the doctrine of the secular cooling and contraction of the earth, which is currently adopted in so many of the physical sciences.

If it may be shown, when we determine the density, pressure and most probable distribution of temperature within the earth, that no circulation of convection currents has taken place since the globe attained approximately its present dimensions, that the effect of secular cooling is therefore sensible only in the crust, and that no deep-seated contraction has occurred since the earliest geological time, we shall be obliged to conclude that other causes should be found which are adequate to account for the phenomena heretofore explained by the effects of secular cooling. In particular it becomes advisable to subject the doctrine of contraction to a most searching examination and crucial test, in order to ascertain what justification

there is for the premises which have been so long adopted in geology and the related sciences. And to make the results of this criterion as convincing as possible, it becomes necessary to adopt mathematical methods, which inspire the greatest confidence in the final conclusions.

So long as contraction was the only available explanation of earthquakes and mountain formation, and no serious doubt had arisen as to the reality of the assigned cause, it seemed legitimate to adhere to the traditional theories of the physics of the globe. But since a different theory has been developed in the paper on "The Cause of Earthquakes, Mountain Formation and kindred phenomena connected with the Physics of the Earth," which explains the observed phenomena by the effects of water vapor accumulating beneath the earth's crust, and seems to be justified by the harmonious concordance of many facts not otherwise intelligible, it appears necessary to re-examine the foundations of the earlier reasoning.

It is true that the traditional theories were rejected in the paper on the cause of earthquakes, for reasons there assigned; but this step is a highly important one, and as the evidence may not be entirely convincing to others, it seems advisable to give a more connected view of the physical grounds on which the step was taken. The general grounds assigned in the former paper need not be repeated here; it is sufficient to recall that they were based partly on the principles of probability and partly on observed phenomena which appeared to admit of but one interpretation.

The paper on the cause of earthquakes grew out of certain phenomena observed during the great earthquake of San Francisco, and was a natural continuation of the previous work on the "Physical Constitution of the Heavenly Bodies" (cf. *A. N.*, 3992, 4053, 4104, 4152). As a result of these researches on the internal state of the heavenly bodies, the writer reached the conclusion that no convection currents exist within the earth, nor have such currents been possible at any time since the globe developed a density comparable to that which it has at present. It was therefore inferred that the cooling extends only through a very thin crust, and consequently the earth is not now appreciably contracting; nor has the contraction been sensible at any time since the terrestrial spheroid attained

approximately its present dimensions. This conclusion was essentially independent of the encrustation, and rested primarily on the resistance to the supposed convection movements caused by the pressure, which is so great as to make all the matter in the deeper portions of the globe behave as an aeolotropic elastic solid. The matter thus made effectively rigid by pressure, could cool only by conduction, and that process is so excessively slow and the heat transferred by it so small in amount as to render it of little effect in the postulated contraction of the earth.

In the former paper arguments were adduced to show that earthquakes and mountain formation depend principally on the secular leakage of the ocean bottoms, and not on the shrinkage of the globe. An attempt was made to justify this inference by an appeal to the observed lay of the mountains parallel to the sea coasts, and the recognized connection between volcanoes, earthquakes and mountain formation. Mention was also made of the inadequacy of the contraction theory to account for the height of mountains, and their congested distribution; and of various other considerations, such as the observed elevation of the sea coasts by earthquakes and the sinking of the adjacent sea bottom shown by the accompanying seismic sea waves. We shall now examine more at length the physical questions connected with the temperature of the earth, and this will afford a basis for judging of the validity of current theories, as well as of certain conclusions respecting seismological problems reached in the former paper.

§ 2. *The Probable Law of Temperature within the Earth.*

The exact process by which the matter of the earth was gathered together and formed into the spheroid which we now inhabit is quite unknown, and one can conceive of what probably took place only by means of dynamical principles applied to ideal conditions offering by analogy a greater or less degree of probability. In this way well guided imaginative conceptions may enable us to approximate the former physical conditions of our planet. For example, it is not likely that the earth as we now find it was formed very suddenly, all the material being brought together so rapidly that but little of the heat of condensation escaped into space. Neither is it probable that the process of agglomeration was so excessively slow that nearly

all the heat of condensation escaped from the surface by radiation through the atmosphere, thus leaving the slowly-accumulated nucleus within at low temperature. In fact this last view seems to be effectively contradicted by the observed internal heat of the globe; and if heat was retained in the layers just beneath the crust, it must likewise have been accumulated throughout the whole nucleus.

It is much more likely that the agglomeration went on with moderate rapidity, so that the primitive globe in formation cooled about as rapidly as a condensing mass of monatomic gas would do under like conditions. Such a gaseous globe retains a little over one half of the heat of condensation. There are many indications that the sun is such a gaseous globe, and the constitution of Jupiter and Saturn probably is more or less similar. It seems likely that in the formation of the earth the meteorites and finer planetary dust came together at such a rate that the whole new planet thus constituted was made to glow with maximum temperature at the centre, as in the case of a sphere of monatomic gas in a state of equilibrium under its own gravitation. Then as the planet grew in mass by the addition of other meteoritic materials, the pressure augmented also, and eventually became so great as to prevent circulation of convection currents. At length the surface gradually cooled by radiation, grew dense and solid, and thus finally arose the encrusted earth.

It must be remembered that until the earth attained a mass of considerable magnitude, the matter falling into it would not be heated to a very high temperature; for in the early stages of the planet the central temperatures would not be high, nor would the force of gravity be intense enough to condense greatly the central nucleus. But as the mass gradually grew in size, the force of gravity would naturally augment, and the temperature rise accordingly. The rise of temperature would take place throughout the central mass by the condensation of the nucleus under increasing pressure; and the deeper down the matter which condensed, the less of the resulting heat would escape to the surface. Thus when the impacts became more and more violent, under increasing gravity, and the surface temperature was much augmented, the central temperature would rise in nearly the same proportion; so that the central temperature would always be the maximum. Yet it is clear that as

we approach the surface the fall of temperature would be slow in all the inner shells of the nucleus. In fact a considerable sphere at the centre would have nearly uniform temperature. But the central temperature could not be lower than that of the enclosing shells; for, if so, the heat would flow towards the centre, and when uniformity was established throughout the nucleus, the flow would start again towards the surface, still leaving the nucleus the hottest part of the sphere.

If some such process be the way in which our globe condensed, it will follow that the temperature is nearly uniform in a central nucleus of considerable size; but towards the surface the fall of temperature would become much more rapid. The curve of temperature thus inferred for the epoch of consolidation corresponds closely to that of an ellipse, in which the semi-axis major represents the radius of the earth, and the semi-axis minor the temperature at the centre. We cannot, to be sure, feel entirely confident that this is the *exact* distribution of temperature within the earth; but it is quite clear that the curve is of this general form, and no doubt an elliptical distribution of temperature will give a close approximation to the truth, which probably is all we can hope for at present. Thus we have established one approximate criterion for the internal distribution of the terrestrial temperature.

The other important criterion is quantitative in character, and is to the effect that one half of the primordial heat of condensation still remains stored up in the globe. This is shown by the following general formula:

$$\frac{Q}{W} = \frac{k - \epsilon}{k - 1}, \tag{1}$$

where Q is the quantity of heat radiated away, W the total amount of work done by gravity, k the ratio of the specific heat of a gas under constant pressure to that under constant volume, and ϵ is the exponent 4/3, in the adiabatic formula $pv^{\frac{4}{3}} = C$ (cf. *A. N.*, 4053, or Ritter's "Auwendungen der Mechanischen Wärmetheorie auf Kosmologische Probleme," Leipzig, 1882).

The temperature attained in the development of the earth must have been very great for all the inner portions, and hence we need not hesitate to adopt the monatomic theory as being most nearly

applicable to these extreme conditions. Accordingly, with $k = 1\ 2/3$, we have $Q/W = 1/2$; and we see that only one half of the heat of condensation has been radiated away, and an equal amount remains stored up in the condensing mass. We must then draw the temperature curve so as to fulfill these two conditions: an elliptical distribution, constructed on an absolute scale such that one half of the primordial heat of condensation is still stored up in the earth.

If it be urged that the earth's matter was not sufficiently heated to be monatomic throughout its whole history, we may recall that when $k = 1.4$, as in common air and most gases, the amount of heat stored up is about 81 per cent. (cf. *A. N.*, 4053); but as this biatomic phase would be of short duration, the extra accumulation during early stages would perhaps about compensate for the loss since surface cooling began. Accordingly a secular accumulation of one half of the primordial heat of condensation would seem to be nearly correct.

In his "Auwendungen der Mechanischen Wärmetheorie auf Kosmologische Probleme" ("Baumgärtner's Buchhandlung," Leipzig, 1882), A. Ritter has established the following formula for the condensation of a gaseous sphere:

$$c_p(\Theta_0 - \Theta_1) = A\eta r \qquad (2)$$

where c_p is the specific heat under constant pressure, 0.2375, $\Theta_1 = 273°$, $A = 1/424$, $r = 6{,}370{,}000$ meters, and

$$\eta = \int_0^\rho \left(\frac{g'}{g}\right) d\rho,$$

g being the acceleration of gravity at the surface and g' that at any depth where the radius is ρ. For uniform density

$$\frac{g'}{g} = \frac{\rho}{r},$$

and we have

$$\int_0^r \left(\frac{g'}{g}\right) d\rho = \frac{1}{r}\int_0^r \rho d\rho = \frac{r}{2}, \quad \text{so that} \quad \eta = \tfrac{1}{2}. \qquad (3)$$

By means, however, of a more exact investigation, based on Laplace's law of density, Helmert calculated for Ritter the value $\eta = 0.73$, which is no doubt sufficiently near the truth. Accordingly with these values the above equation (2) gives

$$\Theta_0 = 46{,}455^\circ \text{ C.} = 83{,}619^\circ \text{ Fahr.} \tag{4}$$

Beginning at the centre with a temperature of 83,600° Fahr., we find for the elliptical distribution of temperature within the earth the values shown in the following table. It is found by calculation that this arrangement of the temperature fulfills the two conditions above specified, namely the elliptical distribution, and the following quantitative criterion:

$$\pi(r_i^3 - r_{i-1}^3)\sigma_i\zeta_i^{-1}\Theta_i + \pi(r_{i-1}^3 - r_{i-2}^3)\sigma_{i-1}\zeta_{i-1}^{-1}\Theta_{i-1} + \cdots$$
$$= \pi\sum_{i=1}^{i=i}\left[\left(\frac{r_i}{a}\right)^3 - \left(\frac{r_{i-1}}{a}\right)^3\right]\sigma_i\zeta_i^{-1}\Theta_i = 45{,}000(5.5)\pi. \tag{5}$$

In the second member of this equation the average specific heat of the earth's matter is taken to be 0.2, and the same numerical value is used in evaluating the first member of the expression under the summation sign.

Radius.	Density Water = 1.0.	Pressure in Atmospheres.	Theoretical Rigidity Due to Pressure, that of Nickel Steel = 1.0.	Temperature.
1.0	2.55	1	0.0000	0.0°
0.9	3.75	198,760	0.198760	33500
0.8	4.99	483,691	0.483691	49000
0.7	6.21	842,921	0.842921	59200
0.6	7.38	1,260,966	1.260966	66600
0.5	8.46	1,710,730	1.710730	72500
0.4	9.40	2,152,114	2.152114	77000
0.3	10.12	2,521,620	2.521620	80000
0.2	10.74	2,861,507	2.861507	82500
0.1	11.07	3,050,870	3.050870	83500
0.0	11.21	3,135,727	3.135727	83600

§ 3. *The Laws of Density, Pressure and Theoretical Rigidity Within the Earth.*[1]

Laplace's celebrated law of density for the earth results from an hypothesis introduced into Clairault's general differential equation for the equilibrium of a heterogeneous mass of fluid endowed with a rotatory motion, which permits the integration of the equation in some particular cases, and thus enables the geometer to connect the oblateness of the successive layers of the fluid with the radius of the spheroid, of which the density is supposed to be a function. In default of knowledge Laplace assumed as an hypothesis that the

law of compressibility of the matter, of which before its consolidation the earth consisted, was that the increase of the square of the density is proportional to the increase of the pressure, or $dp = \kappa\sigma d\sigma$, the integrating of which gives (cf. *A. N.*, 3992)

$$\sigma = \frac{Q \sin(qx)}{x} = \frac{\sigma_0 \sin(qx)}{qx}. \tag{6}$$

When calculated numerically the density, pressure and theoretical effective rigidity are found to be as given in the foregoing table (cf. *A. N.*, 3992, 4104).

The hypothesis employed in deducing the rigidity of the earth and other heavenly bodies, namely that the rigidity is proportional to the pressure, has been discussed in *A. N.*, 4152, as follows:

"In ordinary solids such as the metals the property of rigidity is produced by the action of molecular forces which resist deformation. On the other hand the matter within a planet like the earth is really gaseous but above the critical temperature, and therefore in confinement made to behave as an elastic solid wholly by virtue of pressure which brings the molecules within distances at which they again become effective in spite of the high temperature. Thus in cold solids the property of rigidity is due simply to molecular forces which prevent deformation, while for gaseous matter in confinement under such pressure that it acquires the property of an elastic sold, the property of effective rigidity is due wholly to the pressure. In the paper above cited I have therefore taken the rigidity to be directly proportional to the pressure, and ignored all other influences, such as temperature, because by hypothesis the density is assumed to follow Laplace's law, or the monatomic law, in the case of purely gaseous masses, and the temperature is supposed to be conformable to the laws of density.

"This hypothesis seems legitimate, and almost certainly as accurate as Laplace's law and the monatomic law, upon which the calculated pressures depend. Moreover the validity of the hypothesis that the rigidity is proportional to the pressure appears to be confirmed by the close agreement of the numerical values of the earth's rigidity found in this way with those found by the recognized empirical processes depending on the tides and the polar motion."

If this reasoning is justifiable, it becomes possible to calculate the rigidity of the matter at any depth within the earth, and we are enabled to conclude that the yielding of our globe under the influence of tidal forces to which it may be subjected is mainly superficial. The results of these calculations are illustrated by the curves drawn in the accompanying diagram, Fig. *F*.

Observations seem to prove that in transmitting earthquake waves

the globe behaves throughout as a solid; and it must be held therefore that the matter in confinement acts as an æolotropic elastic solid, though if released from pressure it would instantly expand as vapor, owing to the enormously high temperature.

In the paper on the "Cause of Earthquakes," however, it is shown that notwithstanding this general law for the globe as a whole, there is a thin layer just beneath the crust which in seismic disturbances behaves as a fluid; and the disastrous shaking of the earth is due mainly to the enforced movement of currents in this layer. Yet this substratum of fluid is under such great pressure beneath the confining crust that the compressed lava transmits earthquake waves almost as if the globe were solid from the surface to the centre. Thus even this viscous substratum, under the least pressure of any of the heated matter within the globe, is sufficiently rigid to transmit to us faithfully the waves of compression and distortion which have been communicated to it. It is held that the actual rigidity may be greater than that calculated from the pressure, but it can not be less. We are therefore safe in following the rule that the rigidity is everywhere proportional to the pressure, and this gives us a definite view of the condition of the matter in the different layers.

Mr. R. D. Oldham, F.R.S., has shown that, so far as the propagation of earthquake waves enables one to judge (*Quarterly Journal of the Geological Society,* August, 1906), the matter of the earth's interior is essentially homogeneous down to within 0.4 of the radius from the centre, where some change appears to take place. This probably indicates that the nucleus is a magma of all the elements, with the density and rigidity increasing towards the center, owing to the augmentation of pressure; but the cause of the discontinuity about 0.4 of the radius from the center is not yet understood.

On the whole the most remarkable feature of the earth's constitution is the great increase of pressure towards the center. This gives our encrusted planet enormous rigidity and effective strength, or tenacity, to withstand any disrupting force. The average pressure or theoretical rigidity of all the *layers* composing the earth's mass is (cf. *A. N.,* 4104):

$$P = \frac{3}{4\pi r^3}\int_0^x p \cdot 4\pi r^2 x^2 \cdot r dx = \frac{3 \cdot 3(\sigma_0 g)^2 \cdot r \cdot 4\pi r^3}{4\pi r^3 \cdot 2(\sigma_1 g)q^4}\left\{\int_0^x \frac{\sin^2(qx)x^2 dx}{x^2} - \sin^2 q \int_0^x x^2 dx\right\};\text{ and when } x = 1,$$

$$P = \frac{9(\sigma_0 g)^2 r}{2(\sigma_1 g)q^4}\left\{\frac{q - \sin q \cos q}{2q} - \frac{\sin^2 q}{3}\right\} = 748{,}843 \text{ atmospheres.} \quad (7)$$

And the average rigidity of all the earth's *matter* is:

$$P' = \frac{3}{4\pi r^3}\int_0^x p \cdot 4\pi r^2 x^2 \cdot r dx \cdot \sigma = \frac{9(\sigma_0 g)^2 r \sigma_0}{2(\sigma_1 g)q^5 \sigma_1}\left\{\int_0^x \frac{\sin^3(qx)}{qx} \cdot q dx - \frac{\sin^2 q}{q^2}\left[\sin(qx) - qx\cos(qx)\right]\right\} = 1{,}028{,}702 \text{ atmospheres.} \quad (8)$$

The rigidity of steel is generally taken to be 808,000 atmospheres, but that of nickel steel is at least 1,000,000. The true rigidity of the earth probably lies between the limits set above, and it seems certain that it exceeds that of common Bessemer steel.

In these calculations no account is taken of the increase of rigidity due to the earth's solid crust, the effect of which is known to be considerable; for even the viscous layers just beneath the crust remain quiescent except when set in motion by the dreadful paroxysms of an earthquake. So difficult is this motion to effect that the throes thereby arising may perceptibly disturb a whole continent, and become sensible to observation throughout the world.

Accordingly if the matter of the interior, in confinement under great pressure, behaves as an æolotropic elastic solid, with a rigidity depending on the pressure and therefore increasing with the depth, it naturally follows that no currents can circulate at great depths; and we see that it obviously is not true, as some geologists have imagined, that liquid lava is extruded from deep down in our globe. Neither is it permissible to suppose, as Professor Chamberlin has done (cf. "Geology," Vol. I., p. 630, and Vol. II., p. 120), that our present volcanoes had their start at a depth of some 1200 to 1500 miles.

It follows from the theory developed in the paper on the cause of earthquakes that the original roots of volcanoes were but little deeper than the explosive forces which give rise to world-shaking

earthquakes. Observations show that this depth seldom exceeds twenty miles. Not only is there no extrusion of lavas from great depths at present, but it may also be affirmed with equal certainty that there never has been any such deep-seated extrusion since the earliest geological ages, or even since the epoch when our earth had the maximum surface temperature, before the beginning of encrustation. We may in fact feel sure that no currents were stirring at any considerable depth even when the surface was wrapped in flaming fluid, long before encrustation and secular cooling had begun. All the steam and other free vapors once within the planet had already been expelled, and formed about it a dense atmosphere.

Even if the earth had two or three times its present volume, a calculation of the corresponding pressures throughout the mass shows that there would be very little convective movement possible at any considerable depth. It seems to be true therefore that convection has played a very small part in the arrangement of the internal matter of the globe; and one may infer that the denser elements could not settle towards the center, except in the outermost layers. And the most probable view of the matter of the interior is that it is a magma of all the elements, the increase of density towards the center being due to pressure, which is sufficient to cause complete interpenetrability of all substances, especially under the high temperatures there prevailing.

§ 4. *The Hypothesis of Deep Movements Within the Earth Contradicted by Historical and Geological Evidence.*

It is an observed fact, deduced from the study of world-shaking earthquakes, that movements of this character have never been known to originate at greater depth than thirty, or, at the very outside, forty miles. It follows therefore that earthquakes arise either in the crust or in the layer just beneath it. Now if deeper movements of the globe are in progress, some of them would in all probability have been felt within the historical period; for they would not be similar to ordinary world-shaking earthquakes, but would be of much more widespread character, the shock being of more nearly equal intensity throughout the world. No such world-wide disturbance is recorded in the history of the civilized nations, nor is anything transmitted to us by the traditions of barbarous tribes which

may not be explained by ordinary earthquakes. The preservation of the ruins of temples of the classic period alone assures us that no really deep-seated convulsion of the earth has occurred within the last 2,000 or 3,000 years. This general fact seems therefore decidedly adverse to the doctrine of deep-seated movements of the globe.

To be entirely confident, however, that such cataclysms may not occur at very long intervals, it is necessary to consider the indications furnished by the ruins wrought by geological time. The existence of a vast number of more or less unstable natural pinnacles, in the form of columns of weather- and water-worn rock, scattered abundantly in various parts of the earth, all of an age to be reckoned in hundreds of thousands or millions of years, assures us that nothing approaching a deep and powerful convulsion of our planet has taken place within something like a million years. One naturally concludes therefore that such supposed convulsions, which have always been popular in geology, do not really take place at all. The fact that the continents and islands show the preservation of successive species of fossils, arranged in moderately conformable beds, and the recognized proof that the great continents have never greatly changed their places since geological history began, may be said to supply decisive evidence that no deep-seated convulsions, such as Elie de Beaumont and others were accustomed to imagine, ever take place even at periods to be reckoned in millions of years.

All important changes observed in the earth's crust must therefore be ascribed to external agencies, and especially to earthquakes, which originate within forty miles of the surface, and seldom extend to a depth greater than fifteen or twenty miles. Accordingly we may dismiss for the present any further consideration of this problem; but we shall again resume it after we have examined the distribution of temperature and the secular movement of heat deep down in our globe, which will give another proof that the interior of the earth is now and always has been quiescent.

§ 5. *The Secular Propagation of Heat from the Nucleus into the Enclosing Shells would not Give Rise to the Contraction of an Encrusted Planet.*

It was formerly held that the earth was a liquid mass stirred by

convection currents, and thus before encrustation of nearly uniform temperature throughout. This hypothesis lies at the basis of Lord Kelvin's famous paper on the secular cooling of the earth. But in more recent times the conviction has grown that the temperature must have been a maximum at the center, and a minimum at the surface. This law of temperature distribution has been found to be true of all gaseous masses when subjected to strict mathematical inquiry (cf. *A. N.*, 4053, 4104); and it is natural to think that a similar law holds for planets even after they have become encrusted.

Lane first arrived at such views, from his researches on the theory of the sun, in 1869; and subsequent investigators agree that the density, pressure and temperature would be highest at the center (cf. *A. N.*, 4053, 4104). In the paper on the "Physical Constitution of the Heavenly Bodies" (*A. N.*, 4053) reasons are assigned for holding the view that all bodies of considerable size must become monatomic by dissociation of the more complex molecules into atoms at their maximum temperature; and curves are given for the density and temperature corresponding to this condition. It is also shown that after passing through the monatomic condition, encrustation finally results from restricted circulation and surface cooling, which causes great increase of the surface density. If this view be admissible, it will follow that the central temperature is not materially lowered by the cooling incident to the formation of the crust.

We shall therefore be justified in concluding that the monatomic distribution of temperature still holds true approximately in an encrusted planet. But we have already given reasons why the temperature curve, in the case of a body like the earth, which may possibly be of a meteoritic origin, has nearly the form of an ellipse. If we look at the curve for a monatomic distribution of temperature, given in the accompanying plate, right hand upper corner, and imagine that the surface density increases as encrustation advances and the heat flows outward, we shall see that the monatomic curve may easily pass into an ellipse such as was postulated for an encrusted planet. Assuming the earth to be encrusted, and the internal temperature in any section to follow the law of an ellipse changing with the time, the question naturally arises: What would be the changes produced by the steady flow of heat under the conditions assumed by Fourier?

Some prominent geologists believe that the outflow of heat from the nucleus would produce a deep-seated secular contraction such as they imagine might have caused the subsidence of the ocean basins (cf. Chamberlin and Salisbury's "Geology," Vol. I., pp. 563 and 567).

If the initial distribution of temperature in any plane section of the earth corresponds to the ellipse

$$\frac{x^2}{a^2} + \frac{y^2}{a^2(1 - e^2)} = 1, \tag{9}$$

the distribution after a sufficient interval τ may be taken to be

$$\frac{x^2}{a'^2} + \frac{y^2}{a'^2(1 - e'^2)} = 1. \tag{10}$$

In other words the form and dimensions of the ellipse will change with the time. The two ellipses will intersect at four points, and if they be revolved about the common minor axis, these points of intersection generate circles of no change of temperature; the points are given by the condition

$$x^2\left(\frac{1}{a^2} - \frac{1}{a'^2}\right) + y^2\left(\frac{1}{a^2(1 - e^2)} - \frac{1}{a'^2(1 - e'^2)}\right) = 0. \tag{11}$$

Here x becomes identical with the radius of the circle about the

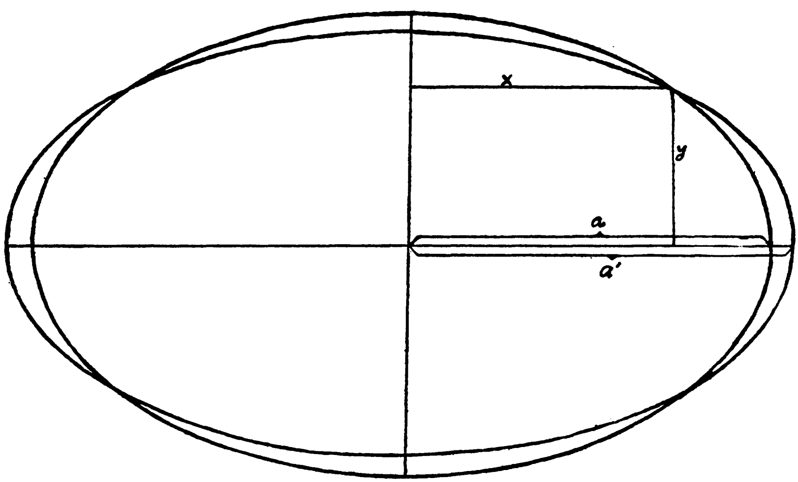

FIG. 1. Section of Ellipsoids.

y-axis, and may be calculated when a, a', e and e' are known, by substituting the value of y in the original equation of the ellipse (9).

Now to show that no change of volume occurs by this propagation of heat from the center outwards, we may observe:

1. That although the major axis of the heat ellipsoid enlarges with the time, the minor axis diminishes, so that except for the slight loss at the surface the volume of the heat ellipsoid remains unchanged, and no heat escapes into outer space; hence there is a change of distribution but not in the total quantity of heat.

2. As this transfer takes place under the confinement of the crust and subjacent layers resting upon the nucleus, the change is necessarily made in such a way as not to do work upon bodies external to the thermodynamic system; nor is work done upon the thermodynamic system itself by external bodies. In either case the constancy of the amount of energy stored up would be altered, which is contrary to the hypothesis.

Any spherical shell $4\pi r^2 dr$, outside of the sphere of no change of temperature, already defined, would have another corresponding shell inside, in which the changes of volume would be equal but of opposite sign to that of the first. Therefore in general we should have

$$4\pi \sum_{i=-i}^{i=+i} r_i^2 dx_i \sigma_i \zeta_i^{-1} d\Theta_i = 0, \tag{12}$$

where $d\Theta_i$ is the change of temperature experienced by any shell, of density σ_i, and specific heat ζ_i. Hence denoting the variation of the elements of volume by δ, we should have, since the change of volume is directly proportional to the change of temperature,

$$\sum_{i=-i}^{i=+i} \delta(dV_i) = 0. \tag{13}$$

The conclusions thus briefly indicated may be stated otherwise as follows:

1. The inner shells of the nucleus, having lost heat, might shrink under the pressure to which they are subjected.

2. The outer shells of the nucleus, having gained heat, would have to expand, or the internal tension and latent heat would have to increase. This would be relieved either by bursting the crust, or

by molecular yielding towards the nucleus, which furnished the heat that caused the expansion.

3. Now to burst the crust would be doing external work. Also since the crust is very strong and its substratum deep, the movement of these superincumbent layers would be very difficult, and involve the expenditure of much energy. The easiest mode of adjusting the tension therefore would be by the molecular movement in the outer shells towards the inner shells of the nucleus, which have shrunk by loss of heat, and in such an adjustment the crust would not be disturbed.

4. No surface disturbances traceable to deep nuclear movements have occurred within the historical period, and geological evidence shows the fixity of the continents throughout all geological time. Therefore we may hold that earthquakes arising in the superficial layers are the only causes which have been active in shaping the topography of the surface since the moon was separated from the globe.

5. Since the effect of radial shrinkage in 100 million years is shown to be very small, different estimates ranging from 0.26 to 1.16 miles (cf. Chamberlin and Salisbury's "Geology," Vol. I., p. 573), it seems absolutely certain that progressive diffusion of heat deep down in the earth could produce no sensible effect at the surface.

Speaking of these effects of secular cooling, Chamberlin and Salisbury remark that "they are exceedingly small. Unless there is a very serious error in the estimated rate of thermal loss, or in the coefficients of expansion, cooling would seem to be a very inadequate cause for the shrinkage which the mountain foldings, overthrust faults, and other deformations imply. This inadequacy has been strongly urged by Fisher[1] and by Dutton.[2] In view of the apparent incompetency of external loss of heat, the possibilities of distortion from other causes invite consideration."

Thus the opinion here expressed is favorable to the views developed in the present investigation. Can it then be that the present negation of deep-seated movement since the earliest geological time is without significance in the argument against the theory of the

[1] "Physics of the Earth's Crust," Chap. VIII.

[2] *Penn. Monthly,* Philadelphia, May, 1876.

secular contraction of the globe? Does not the absence of such movement indicate that the effect of such cooling and contraction is wholly inappreciable?

It may be remarked also that the supposed sensible shrinkage is contrary to our hypothesis, based on what appear to be highly probable conditions, namely that no external work is done, but only an interchange effected between the central and peripheral parts of an essentially adiabatic system. On these several grounds therefore it is impossible to entertain the view that the shrinkage or movement of matter deep down in the earth ever exerts a sensible influence at the surface. The detachment of the main body of the matter composing the moon from the vast depression now occupied by the Pacific Ocean, with opposite tidal fragments from the Atlantic, is a much more probable view of the origin of the principal oceanic basins. The levels were no doubt much restored by the plasticity of the material and the subsequent action of the water and atmosphere, but earthquake forces on the other hand have largely counteracted this tendency to uniformity.[1]

§ 6. *Why the Figure of the Earth can never Have Tended to the Tetrahedral Form.*

It is not without considerable surprise that thoughtful students of the physics of the earth have noticed in recent years the recurrence of the suggestion that the original form of the earth was that of a tetrahedron. It is difficult to understand what there is in this improbable conjecture to render it attractive to some minds. But such an hypothesis may no doubt be compared with Kepler's speculations on the regular solids, before the discovery of the true laws of the planetary motions. Kepler's hypothesis was set forth in the *Mysterium Cosmographicum*, 1596, and as given by Whewell in the "History of the Inductive Sciences," Vol. I., p. 416, is as follows:

"The orbit of the earth is a circle; round the sphere to which this circle belongs describe a dodecahedron; the sphere including this will give the orbit of Mars. Round Mars describe a tetrahedron; the circle including this

[1] Since this paper was completed I have received from Professor W. H. Pickering a copy of a suggestive paper, just published in the *Journal of Geology*, in which he deals with the origin of the moon. Many of his views are similar to those here adopted. The suggestion that the moon originated in the Pacific Ocean is due to Rev. O. Fisher, who published it in *Nature*, Jan., 1882, Vol. XXV, p. 243, and again in the second edition of the "Physics of the Earth's Crust," Chap. XXV.

will be the orbit of Jupiter. Describe a cube round Jupiter's orbit; the orbit including this will be the orbit of Saturn. Now inscribe in the earth's orbit an icosahedron; the circle inscribed in it will be the orbit of Venus. Inscribe an octahedron in the orbit of Venus; the circle inscribed in it will be Mercury's orbit. This is the reason of the number of the planets."

In this last line Kepler alludes to the five kinds of polyhedral bodies, known as the only "regular solids," corresponding to the five planets, besides the earth, which were then known.

When we consider these early views of Kepler in the light of the true laws of nature, nothing so much impresses us as the highly artificial character of the suggested cosmical system. But as the ancients had considered the heavens to be made up of spheres of crystal and glass, the contrast with actual nature implied in the system proposed was much less apparent in Kepler's time than in our own, because the heavens were then, through the influence of the Greeks, still viewed largely as a work of art.

The appearance in this late age of the doctrine of a terrestrial tetrahedron, however, is very remarkable. The earth has been known to be a spheroid differing but little from a sphere since 500 B. C., and the law of gravity by which Newton established the cause of the observed form of the globe has been universally recognized for over 220 years. As the earth has always been highly heated within, one can not doubt that the doctrine of fluidity as applied to it is valid. And the form of the surface ought not only to be spheroidal now, but also throughout the whole past history of our globe. This view is likewise confirmed by the figures of the other planets in space, which have been carefully investigated by astronomers ever since the invention of the telescope by Galileo in 1610.

Moreover Tresca's experiments showed that under great pressure all matter behaves as fluid. It is easily shown that a column of the stiffest granite or steel would not stand over five miles high, without crushing and vaporizing at the base. The column would begin to yield when the weight became sufficient to overcome the molecular forces of the material. A solid pyramid would resist crushing to much greater height than a shaft of uniform diameter, but the principle is the same; and no great height would be attained before even a pyramid of the hardest material would begin to spread at the base and flow, from its own weight. Thus there is a limit to the height

at which mountains would stand, but it seems not to be attained on our actual earth. We conclude therefore that even if the earth were as stiff as steel and given the tetrahedral form, the corners would be crushed down and the figure rapidly rounded up under its own attraction, and this deformation would also develop much internal heat. As the earth, assumed to be cold, could not maintain the tetrahedral form when once given it, it certainly would not tend to acquire it with all except a thin crust at high temperature and kept rigid only by pressure. The hypothesis of an original tetrahedral form for the earth must therefore be dismissed as not even a plausible delusion.

§ 7. *The Continental and Oceanic Features of the Terrestrial Spheroid Probably Depend on the Ruptures Produced when the Moon was Formed, and the Smaller Details of the Surface are due to Modifications of the Crust Made by Earthquake Forces Acting in the Underlying Substratum.*

If therefore on the one hand no movements originate deep down in the earth, and the effects of secular cooling at great depths have little or no influence in deforming the surface, while on the other it is shown that there never was a tendency for the earth's mass to assume the tetrahedral form, it follows that the details of the terrestrial spheroid must be explained by forces acting only in the layer just beneath the crust. To suppose that any tendency to a tetrahedral form can have modified the earth's surface is equivalent to the admission that the molecular forces are powerful, in shaping the crust, in comparison with the effects of gravity. Such a view, however, is known to be untenable, because under great pressure all bodies yield and flow like wax, as was found in Tresca's experiments on the hardest substances, to which allusion has already been made (cf. Tresca and St. Vènant, "Sur l'écoulement des corps solides," *Mémoires des Savants Étranges,* Académie des Sciences de Paris, vols. 18 and 20).

The details of the lithosphere must therefore have been shaped by forces acting beneath the crust, and such depressions of level as origially resulted from the detachment of the moon from the earth. That the moon was originally derived from the rupture of the primitive earth-mass seems to be conclusively proved by Professor Sir G. H. Darwin's celebrated researches on this subject. We do not know at what stage the rupture occurred, nor how much larger in volume the

earth then was than it is now; but the separation probably took place in the earlier history of our planet, before encrustation had begun.

The Rev. O. Fisher has calculated that a layer of matter of the density of granite (2.68) no more than 31 miles thick, taken from the outside of our globe, would furnish a mass equivalent to that of the moon. If the earth's radius was then larger than at present, the layer could be correspondingly thinner; and it probably was sensibly larger then than it is now, though certainly not by so much as 25 per cent. As the rupture is supposed to have originated under the disturbing action of the solar tides, the tidally detached mass would not come from the entire hemispheres, but mainly from the tidal protuberances of the two sides, towards and from the sun. When the matter had been detached most of it was at length gathered together and formed into a satellite, but some considerable masses no doubt again fell back to the earth. It seems most likely that the oceanic depressions and continental platforms originated largely in the genesis of the moon. Part of the present distribution of these features on our globe is thus the work of pure chance, but others, as the Pacific, Indian and Atlantic oceans, probably represent the primitive sinks left by the original disruption. The inequalities remaining after certain masses had again united with the earth probably gave the foundations on which the continents and oceans have since been built. It is most unlikely that such a disruption could occur without leaving oceanic basins, and the Pacific and Indian oceans are evidently the area from which the matter of the moon was mainly derived. Instead of a uniform layer 30 or 35 miles deep, a hemispherical meniscus 50 or 100 miles deep at the center, and thinning out at the edges is naturally suggested.

Great modification and leveling of the inequalities of the basins would naturally be effected by the precipitation of some of the detached masses, and by the enormous bodily tides then at work upon the globe, which was no doubt still largely molten or but thinly encrusted. The long continuation of tidal action would largely smooth out the inequalities in the earth's surface, but it seems almost impossible that it could entirely remove the basins left by the detachment of the matter now forming the moon.

This, then, seems to be the most probable origin of the oceanic

basins, and continental platforms; and we probably are not justified in ascribing any sensible part of these inequalities of level to deep seated shrinkage of particular segments. For we have seen that the general shrinkage is quite incapable of producing such large effects, and there is still less reason why certain segments should shrink so much more than others. The average depth of 2.5 miles for the Pacific Ocean can not well be explained by shrinkage. It appears therefore that the great inequalities of the earth's surface resulted from the formative processes involved in the detachment of the moon, while the smaller inequalities such as mountains, high plateaus, and deep ocean troughs and abysses have been produced mainly by earthquakes acting in the layer just beneath the crust. In this way we may legitimately explain all the leading features of the earth's surface; but it is obvious that we cannot give the details involved in the formation of each continent and ocean, because there is no way of retracing this early history of our planet.

II. On the Secular Cooling of the Earth.

§ 8. *Analytical Theory of the Propagation of Heat in Solid Bodies Applied to the Secular Cooling of the Terrestrial Globe.*

This subject was first treated with characteristic penetration by Fourier, in a memoir entitled "Le Refroidissement Seculaire du Globe Terrestre," communicated to the Philomathique Society of Paris in 1820 (cf. "Oeuvres de Fourier," Tome II, pp. 271–288). It had, however, already been touched upon in the "Théorie Analytique de la Chaleur" (chap. lx., § II., p. 427 et seq.), which, after a delay of some 15 years, was finally published in 1822.

Lord Kelvin's famous discussion of the "Secular Cooling of the Earth" (Appendix D, Thomson and Tait's "Nat. Phil.," Vol. I., Part II.) is based on Fourier's methods; but the constants were carefully determined from new experiments on underground temperature, which gave the conductivity of average rock, and thus made possible important estimates of the age of the earth. Rev. O. Fisher has also treated this and many other questions in his valuable and suggestive work on the "Physics of the Earth's Crust" (second edition).

The mathematical treatment consists in determining by Fourier's fundamental equations the actual temperature at any point in a solid

extending to infinity in all directions, on the supposition that at an assumed initial epoch the temperature had two different constant values on the two sides of a certain infinite plane; and in finding at the same time the rate of variation of temperature from point to point in the solid. To these ends Fourier has demonstrated the following familiar equation for the linear conduction of heat (" Oeuvres de Fourier," Tome II., p. 273).

$$\frac{d\Theta}{dt} = \kappa \frac{d^2\Theta}{dx^2}. \tag{14}$$

In this equation Θ denotes the temperature for the depth x, at the time t, so that x is the distance of any point from the middle plane, and κ is the conductivity of the solid rock composing the crust, measured in terms of the thermal capacity of the unity of bulk; that is, κ is equal to the number of units of heat which would pass across one square foot of a plate of rock one foot thick in a year, when the two faces of the rock are maintained at temperatures differing by 1° Fahr., the unit of heat being the amount required to raise one cubic foot of the rock through 1° Fahr. By careful experimental observations on several kinds of rock *in situ* Lord Kelvin found that $\kappa = 400$ (cf. " Théorie Analytique de la Chaleur," Chap. lx., § II.; and especially " Le Refroidissement Seculaire du Globe Terrestre," " Oeuvres de Fourier," Tome II., pp. 271–288; Thomson & Tait's " Nat. Phil.," Vol. I., Part II., Appendix D; Fisher's " Physics of the Earth's Crust," second edition, p. 67 et seq.).

If α, β, γ be any arbitary constants whatever, and $f(\alpha, \beta, \gamma)$ a function of these quantities, and x, y, z the coördinates of any point of the infinite solid, the general differential equation for the propagation of heat is

$$\frac{d\Theta}{dt} = \kappa\left(\frac{\partial^2\Theta}{\partial x^2} + \frac{\partial^2\Theta}{\partial y^2} + \frac{\partial^2\Theta}{\partial z^2}\right). \tag{A}$$

And the general integral applicable to the most varied cases, subject to the appropriate surface conditions, indicated by the physical nature of the problem, is

$$\Theta = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} t^{-\frac{3}{2}} \cdot e^{-\frac{\{(\alpha-x)^2+(\beta-y)^2+(\gamma-z)^2\}}{4t}} \cdot f(\alpha, \beta, \gamma)\, d\alpha\, d\beta\, d\gamma. \tag{B}$$

When the diffusion of heat takes place in every direction the state of the solid is represented by the integral

$$\Theta = \frac{1}{2^3(\pi\kappa t)^{\frac{3}{2}}} \int\int\int e^{-\frac{\{(\alpha-x)^2+(\beta-y)^2+(\gamma-z)^2\}}{4\kappa t}} \cdot f(\alpha, \beta, \gamma) d\alpha d\beta d\gamma. \quad (C)$$

If the initial heat is contained in a determinate portion of the solid mass, one must take account of the limits which include this heated part, and the quantities α, β, γ, which vary under the integral sign, can not take values exceeding these limits (cf. "Théorie Analytique de la Chaleur," Chap. lx., p. 445). In the case of a symmetrical body like the terrestrial spheroid, it is usual to take the internal distribution of heat to be symmetrical about the center of gravity, which greatly simplifies the general problem. Observations made in many lands indicate that the isothermal surfaces are about equally near the surface at all places, except for the effects of unequal conductivity in the crust; and hence the symmetrical distribution of heat assumed to hold true within the globe seems to be justified. The probable mode of formation of the earth, and the long period during which it has existed, give other grounds for the hypothesis of a symmetrical distribution of the primordial heat about the center of gravity; the unequal temperatures near the surface, due to unequal conductivity in cooling, being confined to a shallow layer of very small extent compared to the globe as a whole. In treating of the heat flowing outward from the center of a symmetrical body like the earth, it thus becomes sufficient to consider the propagation of heat in a single direction normal to the surface. The triple integral is thus reduced to a single integral corresponding to the single variable coördinate, as in the differential equation (14).

The form given the equations by Lord Kelvin and Rev. O. Fisher is but slightly different from that originally used by Fourier, who was occupied with the subject for more than a quarter of a century; but as Lord Kelvin determined the constant of conduction with great accuracy, and also carefully investigated the observed average rate of the increase of temperature with the depth, we shall generally follow his notation, which will also facilitate the comparison of his results with those here obtained.

The rate of variation of the temperature per unit of length perpendicular to the isothermal plane is

$$\frac{d\Theta}{dx}=\frac{V}{\sqrt{\pi\kappa t}}e^{-\frac{x^2}{4\kappa t}}; \tag{15}$$

and the temperature at any point (x, t) in the solid is

$$\Theta=\Theta_0+\frac{2V}{\sqrt{\pi}}\int_0^{\frac{x}{2\sqrt{\kappa t}}}e^{-z^2}dz. \tag{16}$$

In these equations $V=$ half the difference of the two initial temperature and $\Theta_0=$ their arithmetical mean.

It may easily be proved by differentiation that the expression for Θ satisfies Fourier's equation (14).

When $t=0$, the expression for Θ, x being positive, becomes

$$\Theta_0+\frac{2V}{\sqrt{\pi}}\int_0^{\infty}e^{-z^2}dz=\Theta_0+\frac{2V}{\sqrt{\pi}}\cdot\tfrac{1}{2}\sqrt{\pi}=\Theta_0+V. \tag{17}$$

For all negative values of x, $\Theta=\Theta_0-V$.

By differentiating (16) we obtain $\frac{d\Theta}{dx}$; and it is easy to see that for all values of t, the second term of the right member of this equation has equal positive and negative values for corresponding values of x. Taking Lord Kelvin's experimental value of the conductivity, $\kappa=400$, equation (15) is reduced to the form

$$\frac{d\Theta}{dx}=\frac{1}{35\cdot 4}\frac{V}{\sqrt{t}}e^{-\frac{x^2}{1600t}}. \tag{18}$$

Lord Kelvin remarks that if $t=1{,}000$ million years, and $x>3{,}000{,}000$ feet, the exponential factor becomes less than $e^{-5.6}$, or less than $1/270$, which may be neglected as insensible. This indicates that at depths greater than 568 miles the rate of variation of temperature does not become sensible in 1,000 million years. A temperature gradient thus exists only within a thin crust, and the influence of curvature of the surface may be neglected; so that the solution in the case of Fourier's infinite solid becomes immediately applicable to the cooling of the earth.

If we take $t=100$ million years from the beginning of the radiation,

$$\frac{d\Theta}{dx}=\frac{1}{35\cdot 4\times 10^5}Ve^{-\frac{x^2}{1600\times 10^8}}. \tag{19}$$

By platting this equation Lord Kelvin found the curve for the rate of variation of temperature in the earth, 100 million years after the initial epoch, on the hypothesis that the surface temperature was suddenly lowered V degrees, and kept at this figure, so as to produce a steady flow of heat from within outward.

He took $V = 7000^\circ$ Fahr.

§ 9. *The Age of the Earth's Consolidation Calculated by the Fourier-Kelvin Method.*

Considering the earth to be a sphere of the same conductivity as average rock, we have for the rate of augmentation of temperature downward

$$\frac{d\Theta}{dx} = \frac{V}{\sqrt{\pi\kappa t}} e^{-\frac{x^2}{4\kappa t}} = \frac{1}{35 \cdot 4} \frac{V}{\sqrt{t}} e^{-\frac{x^2}{1600 t}}, \tag{18}$$

κ being 400, when the units are the foot, year, and degree Fahrenheit. Solving this equation for t, and putting $V = 7000^\circ$ Fahr., we have

$$t = \left(\frac{51\,V}{35 \cdot 4}\right)^2 = 101{,}673{,}000 \text{ years.} \tag{20}$$

This is Lord Kelvin's method of estimating the age of the earth, or the duration since the beginning of the consolidation of the crust, which is supposed to have occurred very soon after the initial epoch.

We have already seen that the assumption of an original uniform temperature for the earth is only a first approximation to the true condition, not justified by a closer examination of the subject. The mathematical theory of the heat distribution in a gaseous globe shows that the temperature increases rapidly towards the center, and hence falls off correspondingly near the surface. Relatively to the average temperature of the whole mass, that of the surface is very low, and that of the center quite high. This is the condition in a gaseous sphere, and it seems certain that it cannot be greatly modified by the surface cooling which leads to encrustation. We have seen that this latter arises mainly from resisted circulation, and retarded supply of heat from the under layers, as the surface density increases. Prior to the beginning of surface cooling the planet passes through a stage of maximum temperature, and heat is both radiated and conducted through to the outer layers; but eventually the resistance to propagation of heat becomes so great that a fall of temperature is inevitable.

In the case of the earth there is excellent reason to conclude that the surface temperature never much exceeded 2000° Fahr.

The experiments of Professors Rücker and Roberts-Austen at the Royal College of Science, London, on basalt or dolerite of Rowley Regis, undertaken at the suggestion of the Rev. O. Fisher, showed that this rock was completely fused at 1688° Fahr. Basalt is a typical rock of the earth's crust, prevalent in nearly all volcanic districts; and it seems probable that a temperature of 2000° Fahr. would therefore not only fuse all the principal rocks of the earth's surface but also reduce many of them to a state of vapor.

The fact that the other planets of our solar system are not at present self-luminous, though the larger masses are known to have high internal temperature, tells against the theory of a very high surface temperature also in the case of the earth. For although we view the other planets at only one stage of their existence, and therefore cannot fully judge of their conditions at other cosmical epochs, yet the absence of self-luminosity when so much heat is known to be stored up within these planets can only indicate that a great lowering of temperature always takes place near the surface, as is also true in a sphere of monatomic gas. Thus it is not probable that even at the maximum the surface temperature of such masses would be very high. There are clear indications that Lord Kelvin's estimate of 7000° Fahr. is much too great; and in all probability we shall not be far wrong in using 2000° as the most acceptable value in all calculations on the secular cooling of the terrestrial globe. The temperature will increase with the depth, but for a shallow layer we may take it to be uniform; the temperature of 2000° then would not correspond exactly to the surface, but rather to the average of a thin sheet forming the boundary of the molten mass. As the outer layer was no doubt agitated from beneath, it would both lack in uniformity of temperature, and also be constantly changing, so that a mean temperature of 2000° Fahr. seems to be the closest approximation we can make to the true conditions.

Using $V = 4000°$ in formula (20), we get $t = 33{,}208{,}850$ years; which is the age of the earth on this hypothesis. When $V = 2500°$ Fahr., we find $t = 12{,}972{,}200$ years. And if $V = 2000°$ Fahr., the result is $t = 8{,}302{,}210$ years, a comparatively short duration. As the

melting temperature of basalt is less than 1688° Fahr., the smaller value for V obviously is to be preferred. Thus the assumed surface temperature of 2000° Fahr. seems sufficiently high, and our most probable age of the earth calculated in this way is

$$t = \left(\frac{51\,V}{35\cdot 4}\right)^2 = 8{,}302{,}210 \text{ years.} \tag{21}$$

Accordingly, we conclude from this Fourier-Kelvin formula that the age of our encrusted planet can scarcely exceed 10 million years, which accords very well with the duration inferred from the theory of the sun's heat (cf. *A.N.*, 4053).

§ 10. *The Age of the Earth's Consolidation Calculated by Fisher's Method.*

The Rev. O. Fisher has developed another method for calculating the age of the earth which we shall now explain. It is in the main independent of Lord Kelvin's procedure based on Fourier's equation for the rate of increase of temperature downward, and has some advantages over it. Fisher's method is treated in Chapter vI., and also in the Appendix, to the second edition of his "Physics of the Earth's Crust." He established the following formulæ:

$$\left.\begin{aligned} V &= 2\mu e^{\mu^2} M\cdot\lambda\left(1 + \frac{y}{k}\right) \\ &= 2\mu e^{\mu^2} M\lambda, \qquad \text{for inert substratum, in which } y = 0. \end{aligned}\right\} \tag{22}$$

$$\beta = \frac{V}{M}\frac{1}{\sqrt{4\kappa t}}, \tag{23}$$

$$k = \mu\sqrt{4\kappa t}, \tag{24}$$

$$M = \int_0^{\mu} e^{-z^2}dz.$$

In these equations μ is a function differing but little from unity; M is the definite integral $\int_0^{\mu} e^{-z^2}dz$; κ the coefficient of conductivity taken to be 400, as in Lord Kelvin's work; k is the thickness of the earth's crust; β the surface rate of augmentation of temperature downward; λ is the latent heat of molten rock measured in terms of the amount of heat required to raise one cubic foot of the rock

through 1° Fahr.; and Λ is the latent heat measured in thermal units centigrade, water being the standard substance. In the appendix, p. 20, Fisher shows that Rücker's experiments make $\Lambda = 49.60$, the corresponding value for water at zero centigrade being 79.25. Taking the mean specific heat of average rock at 0.22, he makes $\lambda = 406°$ Fahr., and $V = 1688°$ Fahr. This is the temperature at which basalt is entirely melted. Finally, the quantity y is a function representing the activity of the substratum, and therefore zero when the layer is inert (cf. Chapter vI., p. 73).

Using these values Fisher finds for an inert substratum, that the true values are:

$\mu = 1.007$; $M = 0.7493736$; and the thickness of the crust

$$k = \frac{51 \times 1688 \times 1.007}{5280 \times 0.74937} = 21.91 \text{ miles.} \tag{25}$$

He concludes that the least thickness of the crust will be $\frac{V}{\beta} = 16.30$ miles, and that the true thickness of the crust will lie between 16.30 and 21.91 miles. If we take $k = 17.5$ miles, which is very near the thickness of the crust indicated by the great earthquake which devastated San Francisco, and apply formula (24) we find for the age of the earth

$$t = \frac{k^2(5280)^2}{\mu^2 4\kappa} = 5,262,170 \text{ years.}$$

Using $k = 21.91$ miles, in the same formula, Fisher finds

$$t = 8,248,380 \text{ years.} \tag{26}$$

This age for the encrustation of the earth seemed to him surprisingly small, and he therefore remarked:

"This is a far shorter period than geological phenomena appear to require, for although it is not possible for them to assign any definite limit to the world's age, we can form some idea of an inferior limit which it must have exceeded. Sir A. Geikie thinks that the stratified rocks alone, which contain organic remains, can not have taken much less than 100 million years for their formation."

The Rev. O. Fisher then proceeds to examine the hypothesis of an energetic substratum, and by this process reaches a greater age for the world. But for reasons pointed out in the previous paper on the cause of earthquakes, the hypothesis of an inert substratum is

obviously the proper one. For the substratum is shown to move only under the throes of an earthquake, and no circulatory movement of lava exists even just beneath the crust. Hence we adhere to the result there obtained, and must consider the significance of the small age of the earth. It will be seen that for a thickness of 22 miles, the age of the earth's consolidation is almost exactly the same as that reached by the use of Lord Kelvin's formula.

§ 11. *Remarkable Agreement of the Times Since the Consolidation of the Globe as Concluded from these Two Methods.*

The result found by Lord Kelvin's method rests upon the observed rate of increase of temperature downward, namely 1° Fahr. for 51 feet, which is about the same as the value used by Fourier nearly a century ago, and not improved upon by the deep borings made in recent years. It also rests upon the assumed surface temperature of 2000° Fahr., which probably is comparatively near the truth. Is it purely an accidental coincidence that with these data one is led by the Fourier-Kelvin formula to an age of 8,302,210 years, while by Fisher's formula, depending on the thickness of the crust essentially verified by earthquake phenomena, one finds the almost identical age of 8,248,380 years? Moderate variations of the data might derange this excellent agreement somewhat, but probably no change of the constants within admissible limits would produce extreme discordance in the resulting ages of the earth. It seems therefore difficult to escape the conclusion that these figures really approximate the true age of our encrusted planet. At least the period since the consolidation is of the order of ten million years.

Different investigators will naturally form different estimates of the age of the earth as found by the several methods of approximation; but it is difficult to see how the larger values formerly current can be justified by physical research based on the propagation of heat involved in the secular cooling of the globe. The writer has not the geological learning requisite for the use of the methods based on sedimentary rocks and their deposits of organic remains, but it seems very doubtful if these methods can lay claim to even approximate accuracy; and to most minds the conclusions drawn from the physical methods will naturally carry much greater weight.

Some considerations, however, based on the probable average

rate of the elevation of the Andes, taken at only one tenth of an inch a year, or ten inches in a century, seem to show that the age of these mighty mountains need not much exceed three million years. In the case of the mountains west of the Rockies a numerical estimate is not quite so easy, but it is doubtful if anything authorizes an estimate exceeding five million years. In this immense period the whole country west of Laramie may have been raised from the sea; in fact this is indicated by the abundant fossils of Saurians in the beds of Wyoming, as well as by the numerous parallel ranges of mountains in Nevada and California, showing the successive recessions of the sea. One is led therefore to think that after all our consolidated globe may not have an age exceeding eight or ten million years. In comparison with the brevity of human history such periods are almost infinite; and so little is known of the rates of variation of organic species under the unknown conditions of the past, that we may well hesitate before assuming longer periods for the life of our encrusted planet.

In contemplating this result we are again confronted with the question of the cosmical significance of radium. Several years ago when the enthusiasm over the radium discoveries was at its height there were those who admitted a terrestrial history of a thousand million years (cf. Professor Sir G. H. Darwin's presidential address to the British Association at Capetown, 1905). But mysterious as radium still remains, it is doubtful if such a view is generally held today. It is a remarkable fact that the more we study radium, the less we seem to really understand the part it plays in cosmical processes. So far at least there is no proof that it exerts any sensible influence, except possibly in chemical transformations.

§ 12. *Some of the Results of the Researches on Radium.*

In spite of the great labor bestowed upon the study of radium by many devoted and enthusiastic investigators, it can hardly be said that we have up to this time any conclusive results as to the cosmical significance of this very wonderful element. The theories of radium disintegration are well known, but not universally accepted. Lord Kelvin is one of those who still ascribe the Sun's heat to the potential energy of the mutual gravitation of its own matter; and he denies that radium plays any appreciable part in solar activity.

Major Dutton tried to explain the activity of volcanoes by means of periodic outbursts produced by radium, but the distribution of these vents along the shores of continents, on islands and in the sea, while none at all break out in the interior of continents, shows that there is a dependence on the oceans, and proves that radium cannot be the active cause in producing eruptions. For the experiments of the Hon. R. J. Strutt have proved that radium is widely distributed in the rocks of the earth's crust, such as granite; but he found on the other hand, that some basalts show scarcely a trace of it. This does not speak favorably for the view that radium is the cause of the earth's internal heat and volcanic outbreaks. For if radium were the cause basalts ought to be rich in the element which had caused the expulsion of this rock from volcanoes; and since all granite contains abundant radium, volcanoes ought to break out in the interior of continents, such as Africa, Australia, North and South America, Europe and Asia; but this is contrary to observation. It is not possible therefore to entertain the view that radium has any sensible connection with volcanic activity.

Of late even the terrestrial origin of radium has seemed doubtful, and in *Nature* of February 1, 1907, Professor J. Jolly, of Dublin, has suggested several considerations indicating that radium may come to us from the sun, in the form of infinitessimal corpuscles, expelled principally by the pressure of the sun's light. So far as we can now see this extra-terrestrial source of radium is by no means improbable. But whether this suggestion be verified by time and experience or not, it seems certain that radium in the earth's crust is essentially dormant; at least it plays little part in the physics of planets such as the earth, except perhaps in chemical transformations.

It probably is not without significance that in order to make the theory harmonize with the observed temperature gradient, Strutt attributes radium only to the crust, and not to the interior matter of the earth. If radium comes from the sun, it would lodge in the oceans, and be carried down into the sedimentary and other rocks, as now observed. In the absence of decisive proof we must suspend judgment, but at present one can only say that there is no evidence that radium is an important agency in cosmical processes witnessed upon our globe. For the sake of comparison, however, we give

Strutt's curve of temperature calculated on the hypothesis that radium in the earth's crust is the principal cause of the observed internal heat of the globe. (*Proc. Roy. Soc.*, Vol. 77, 1906.)

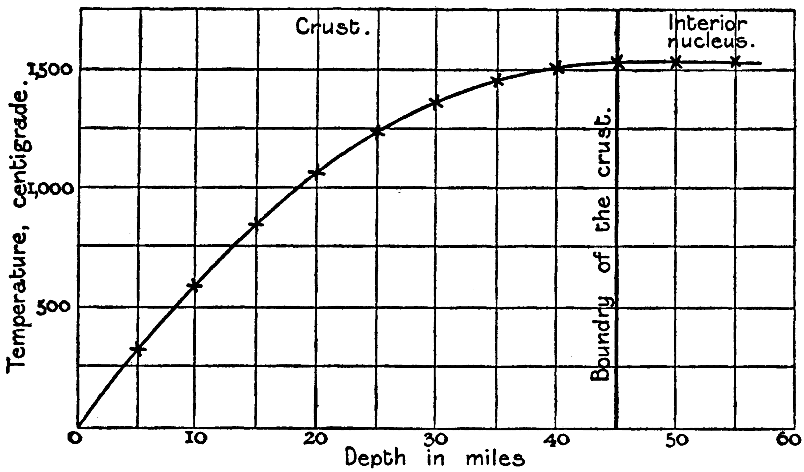

FIG. 2.

III. ON THE AGE OF THE CONSOLIDATION OF THE GLOBE AND ON THE SECOND APPROXIMATION TO THE LAW OF TEMPERATURE NEAR THE SURFACE.

§ 13. *Consideration of the Twelve Fourier Solutions.*

The methods here employed are those of Fourier, with the constants determined by Lord Kelvin. In view of the great uncertainty heretofore prevailing respecting the age of the earth's consolidation, we have thought it advisable to consider in all twelve cases, namely, three distinct times, of 10,100, and 1000 million years each, and four initial temperatures of 2000°, 4000°, 8000° and 12,000° Fahr. respectively. These twelve solutions are illustrated by the diagrams in the accompanying plate. If the earth had been of uniform temperature throughout, no doubt its actual history would be essentially included in one of the accompanying diagrams.

But we have already seen reasons for holding that the central temperature was very high, and the surface temperature quite low; and moreover there is no doubt that the secular cooling is confined almost entirely to the crust. In considering the age of our earth

therefore we may pass over the diagrams which are based on very high initial temperature. In like manner we may reject those diagrams which are based on such long periods as 1000 million years. For the same reasons a period of 100 million years is much too long. It seems certain that the time since the consolidation of the globe is of the order of 10 million years; and that the surface temperature at the initial epoch did not much exceed 2000° Fahr., and it may never have quite equaled this figure.

But as the actual temperature rises downward, not only in virtue of the surface cooling, but also in accordance with the initial distribution of temperature throughout the globe as a whole, before cooling began, we have to consider the effects of a uniform temperature of say 2000°, and of an independent temperature gradient increasing with the depth. The loss of heat now going on is similar to that depending on the gradient alone—small in amount and very uniform in its rate. Each separate part of this double flow implies rise of temperature downward, and thus we may be sure that the true curve of temperature is steeper than those calculated on the hypothesis of uniform temperature. Thus the rate of augmentation of temperature downward also becomes greater than that calculated in the diagram. The effect then of the original independent gradient is to considerably raise the Fourier temperatures at any depth, and to maintain also a larger rate of augmentation of temperature than the calculated rate.

§ 14. *Approximation to the Actual Law of Temperature near the Surface.*

If we take the Fourier gradient established by secular cooling after 10 million years as giving the original rise of temperature within the earth, before cooling began, which in any case can differ but little from the truth, we may calculate the actual distribution of temperature within the earth's crust as follows:

1. Having computed the rate of augmentation of temperature, and by integration, found the curve of temperature itself for a surface temperature of 2000° and a duration of 10 million years, we calculate likewise the same curves for a duration of 20 million years.

2. The difference between these two sets of curves, one for $t = 20$ million, the other for $t = 10$ million years, when carefully

tabulated, and added algebraically to the ordinates of the original Fourier solution, in which the uniform temperature was 2000°, and $t = 10$ million years, gives very nearly the true curve for the temperature near the surface. This is illustrated by Fig. *D*, in the diagram. The formulæ used are:

For the rate of augmentation of temperature

$$\frac{d\Theta}{dx} = \frac{1}{35.4}\frac{V}{\sqrt{t}}e^{-\frac{x^2}{1600t}}, \qquad \frac{d\Theta'}{dx} = \frac{1}{35.4}\frac{V'}{\sqrt{t+\tau}}e^{-\frac{x^2}{1600(t+\tau)}}, \tag{27}$$

where both t and τ are taken to be each 10 million years, and $V = V'$.

For the curve of temperature we have

$$\left.\begin{aligned} \Theta &= \frac{1}{a}\int_0^x \frac{d\Theta}{dx}dx \\ \Theta' &= \frac{1}{a}\int_0^x \frac{d\Theta'}{dx}dx \end{aligned}\right\}. \tag{28}$$

$$\Theta_1 = \frac{1}{a}\int_0^x \frac{d\Theta}{dx}dx + \frac{1}{a}\left\{\int_0^x \frac{d\Theta}{dx}dx - \int_0^x \frac{d\Theta'}{dx}dx\right\} = \Theta + (\Theta - \Theta'), \tag{29}$$

in which $a = 2\sqrt{kt}$ (cf. Appendix *D*, Thomson & Tait's "Nat Phil.," Vol. I., part II., p. 477).

More generally the formulæ become

$$\left.\begin{aligned} \frac{d\Theta}{dx} &= \frac{1}{35.4}\frac{V}{\sqrt{t}}e^{-\frac{x^2}{1600t}}, \\ \frac{d\Theta'}{dx} &= \frac{1}{35.4}\frac{V'}{\sqrt{t+\tau_1}}e^{-\frac{x^2}{1600(t+\tau_1)}}, \\ \frac{d\Theta''}{dx} &= \frac{1}{35.4}\frac{V''}{\sqrt{t+\tau_1+\tau_2}}e^{-\frac{x^2}{1600(t+\tau_1+\tau_2)}}, \\ &\vdots \\ \frac{d\Theta^i}{dx} &= \frac{1}{35.4}\frac{V^i}{\sqrt{t+\tau_1+\tau_2+\cdots+\tau_i}}e^{-\frac{x^2}{1600(t+\tau_1+\tau_2+\ldots+\tau_i)}}. \\ &\text{Or when the times are reckoned from arbitrary epochs} \\ \frac{d\Theta^i}{dx} &= \frac{1}{35.4}\frac{V^i\cdot e^{-\frac{x^2}{1600\{t+(\tau_1-t_1)+(\tau_2-t_2)+\ldots+(\tau_i-t_i)\}}}}{\sqrt{t+(\tau_1-t_1)+(\tau_2-t_2)+\cdots+(\tau_i-t_i)}}. \end{aligned}\right\} \tag{30}$$

And

$$\Theta_i = \frac{1}{a}\int_0^x \frac{d\Theta}{dx}dx + \frac{1}{a}\left\{\int_0^x \frac{d\Theta}{dx}dx - \int_0^x \frac{d\Theta'}{dx}dx\right\} + \frac{1}{a}\left\{\int_0^x \frac{d\Theta'}{dx}dx - \int_0^x \frac{d\Theta''}{dx}dx\right\} + \cdots + \frac{1}{a}\left\{\int_0^x \frac{d\Theta^{i-1}}{dx}dx - \int_0^x \frac{d\Theta^i}{dx}dx\right\}. \quad (31)$$

Finally

$$\Theta_i = \Theta + (\Theta_1 - \Theta_1') + (\Theta_2' - \Theta_2'') + (\Theta_3'' - \Theta_3''') + \cdots + (\Theta_i^{i-1} - \Theta_i^i). \quad (32)$$

the subscripts on the right corresponding to the i arbitrary epochs. In the application of these equations we must remember that this multiple process is valid only for values of x smaller than that corresponding to the maximum of Θ_i. For in Fig. *D*, we see that there is a maximum to the multiple temperature curve, and the true course of it can not be determined beyond this point. The apparent fall of temperature at greater depths indicates the failure of the process. But by taking suitable periods of time, and appropriate values for $V, V', V'', \ldots V^i$, one may approximate the true curve asymptotically near the surface, and carry the determination to any desired depth.

In our present numerical work we have thought it sufficient to take $\tau_1 = 10$ million years, and $V' = V = 2000°$. By carrying this process far enough we may obtain a multiple solution which is almost absolutely rigorous, and it will include all the effects of rising temperature beneath the surface as well as the uniform temperature embraced in the original solution of Fourier. The principal difficulty in extending the method to the propagation of heat at great depths is the uncertainty respecting the original law of temperature within the earth, before encrustation began. But it appears clearly and unmistakably that the true curve of temperature is much steeper than that resulting from the simple Fourier solution. At greater depths the steepness increases more and more, till it finally takes the form of the arc of an ellipse, as already pointed out. The curve is thus concave near the surface, and convex at great depths, so that it has a point of flexure, probably at no very great depth, but the exact location cannot be determined. The simple Fourier solutions always make the curves of temperature convex near the surface, which is a serious defect and introduces discontinuity at greater depths.

It may be noticed that when all the arguments of the times

$\tau_1, \tau_2, \tau_3 \ldots \tau_i$ start from a common epoch $t = 0$, and the functions $V, V', V'', \ldots V^i$ are all equal, the subscripts in the right member of (32) drop out, and the equation reduces to

$$\Theta_i = \Theta + (\Theta - \Theta^i).$$

But in the more general problem the functions $\tau_1, \tau_2, \tau_3, \ldots \tau_i$ date from i chosen epochs, and this gives the means of approximating any curve without change of flexure between $x = 0$, and $x = x$.

§ 15. *Fourier's Methods Adequate for Effecting a Rigorous Solution of the Problem when the Conditions are Known.*

As already remarked the earth is so large and the crust so thin compared to the length of the radius, that the curvature of the surface may be neglected; and the layer of rock considered to extend to infinity in all directions, thus essentially conforming to Fourier's hypothesis of an infinite solid in the form of a flat plane.

Reasons have been assigned for doubting the great age sometimes ascribed to the earth, and it might seem like a waste of effort to draw the curves for the Fourier solutions in the case of such immense periods as 1000 million years; but in view of the great uncertainty heretofore prevailing in regard to the age of the consolidation it appeared advisable to conduct the investigation on the broadest lines. The leading characteristics of these Fourier solutions are shown by the rate of increase of temperature downward, and by the depth at which high temperature is attained. The horizontal scale, representing the depth, is the same in all the curves shown in the diagram; and thus a direct comparison of the effects of the three different periods is possible. In the case of the 1000 million year period the cooling has extended to great depth, more than 445 miles, which exceeds one tenth of the radius; in fact the increase continues downward to about 570 miles, or nearly 0.15 of the radius; but the change of temperature so deep down is excessively slow.

The curves for 100 million years after the initial epoch are naturally much steeper than those just considered, and accord closely with those drawn by Lord Kelvin, who used the same period. In the solution for the interval of 10 million years after the cooling began the curves are naturally very much steeper yet. In fact for this short period the cooling has not yet extended much lower than

40 miles, or about one tenth of that found for the 1000 million year period. The short period thus gives rapid rise of temperature near the surface, while the long periods give slow augmentation of temperature extending to great depths. All the Fourier curves, those for the rate of increase as well as for the temperature, become asymptotic to certain lines, as shown in the diagrams.

We have already considered how to pass from these Fourier solutions to a double solution which will take account of the increase of temperature downward at the initial epoch. This method of superposed or multiple solutions may be applied to all cases, but it has not seemed worth while to consider any case except that with a period of 10 million years and a surface temperature of 2000°. Whether we use the pure Fourier solution, or the compound produced by superposing two solutions of different period, it appears that the actual temperature increases at a nearly uniform rate for a depth of more than 40 miles, after which it is probable that the approximate elliptical law holds true to the center of the planet.

The temperature ellipse is not imagined to extend into the cooled crust, but to begin at the lower boundary of this layer. As we have treated of a superposition of two solutions of different periods, so also we might have compounded three, four or more solutions, with as many independent periods, which would enable us to represent any steady and continuous law of temperature within the earth. If this procedure is justifiable, it will follow that the uniform rise of temperature is nearly maintained for at least a tenth of the radius. Under the circumstances it is not to be hoped that any deviation from the uniform rate of increase near the surface will ever be discovered from experimental measurements of underground temperature. And observations indicating unequal rates at various depths are to be explained by the unequal conductivity of the different layers of the crust, and by fissures filled with hot lava during earthquakes of past geological ages.

From Fig. *D,* in the diagram, we see the principle of the multiple solution illustrated. The difference between the middle and lower curve is the effect of an additional 10 million years. This depression with changed sign should therefore be added to the simple Fourier solution to give the temperature curve under the hypothesis that

there is both a uniform temperature and an independent gradient equivalent to the effects of 10 million years of cooling.

§ 16. *Various Methods for Determining the Depth to Which Cooling has Extended.*

Owing to the causes already indicated it seems reasonably certain that the cooling of the earth has not extended to any great depth. Moreover the original temperature gradient increasing with the depth still exists, but the flow of heat has changed the form of the curve. It will doubtless strike many as a somewhat remarkable fact that Professor Milne finds from earthquake observations that a fairly abrupt transition in the constitution of the crust occurs at a depth of about 30 miles (Bakerian Lecture, *Proc. Roy. Soc.*, 1906, p. 369). A depth of 45 miles was fixed upon for this transition by the Hon. R. J. Strutt, from certain considerations arising in his researches on radium (*Proc. Roy. Soc.*, Vol. 77, 1906, p. 483). Mr. R. D. Oldham finds that below this layer of crust the material of the globe seems to be fairly uniform until we reach great depth, about 0.4 of the radius from the center, where the change in the rate of propagation of earthquake waves shows that some discontinuity intervenes. Strutt remarks that the matter of the interior can scarcely consist mainly of iron, as has been commonly supposed, because with a thin crust of rock this would make the earth's mean density too great.

The ascertained depth of earthquake shocks and the observed rate of propagation of seismic waves both indicate a thin crust, but the phenomena of wave propagation make the thickness of the crust somewhat greater than that derived from the observed depth of earthquake disturbances. This suggests that earthquakes do not originate entirely beneath the crust, but chiefly in its lower layers. From Milne's results we seem justified in concluding that the cooling has not extended much if any below 40 miles, or 1/100th of the radius. The material below that depth acquires its properties mainly from the pressure to which it is subjected.

We have already considered the extension of Fourier's method which would enable us to approximate the true conditions near the surface; and it only remains to add that at greater depths there is a transition to the elliptical law, which holds approximately throughout the nucleus as a whole. There is obviously some uncertainty about

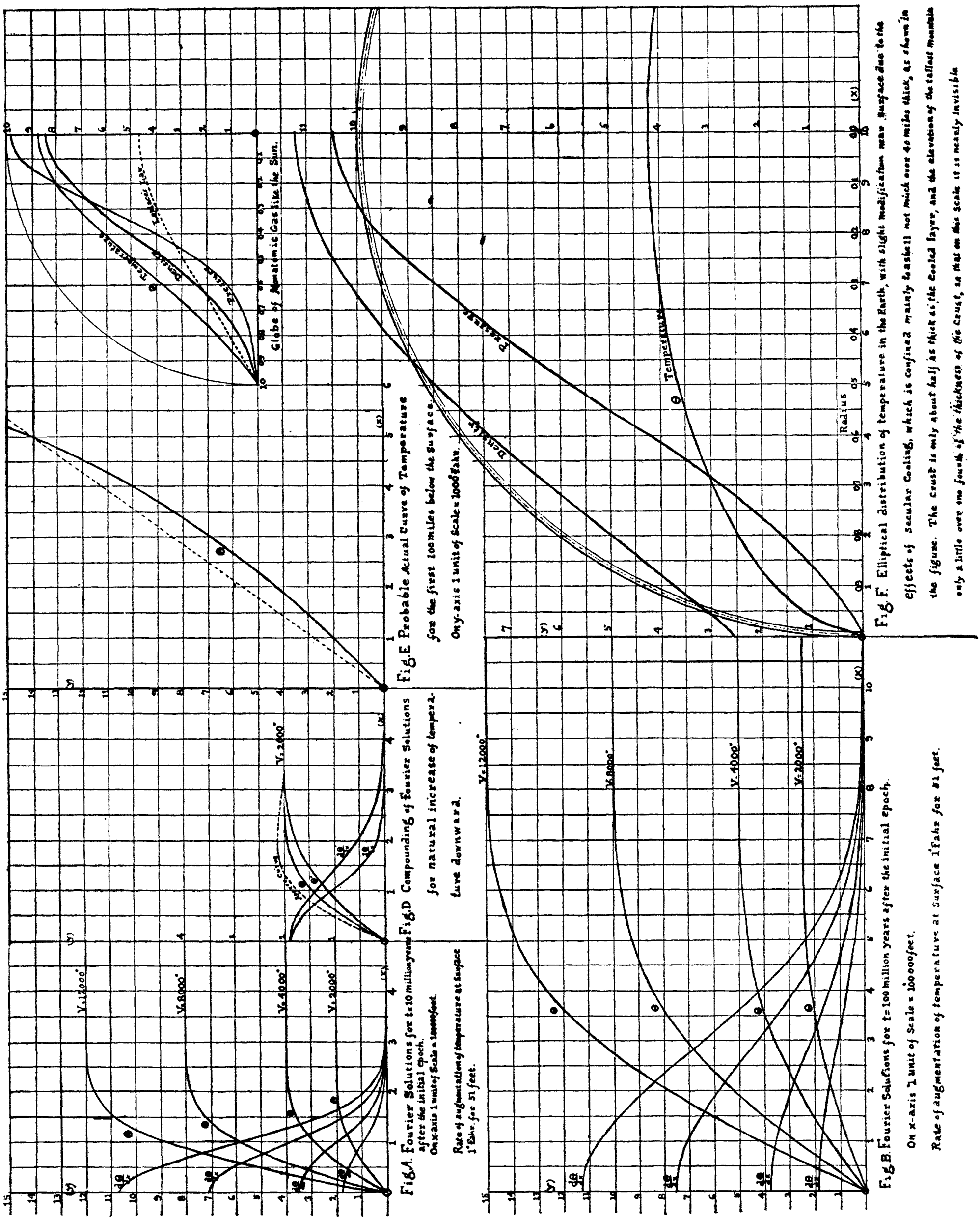

Fig. A. Fourier Solutions for t=10 million years after the initial epoch. On x-axis 1 unit of Scale = 100000 feet. Rate of augmentation of temperature at Surface 1° Fahr. for 51 feet.

Fig. D Compounding of Fourier Solutions for natural increase of temperature downward.

Fig. E Probable Actual Curve of Temperature for the first 100 miles below the Surface. On y-axis 1 unit of Scale = 1000° Fahr.

Fig. B. Fourier Solutions for t=100 million years after the initial epoch. On x-axis 1 unit of Scale = 100000 feet. Rate of augmentation of temperature at Surface 1° Fahr. for 51 feet.

Fig. F. Elliptical distribution of temperature in the Earth, with slight modification near Surface due to the effects of Secular Cooling, which is confined mainly to a shell not much over 40 miles thick, as shown in the figure. The Crust is only about half as thick as the Cooled layer, and the elevation of the tallest mountain only a little over one fourth of the thickness of the Crust, so that on this Scale it is nearly invisible

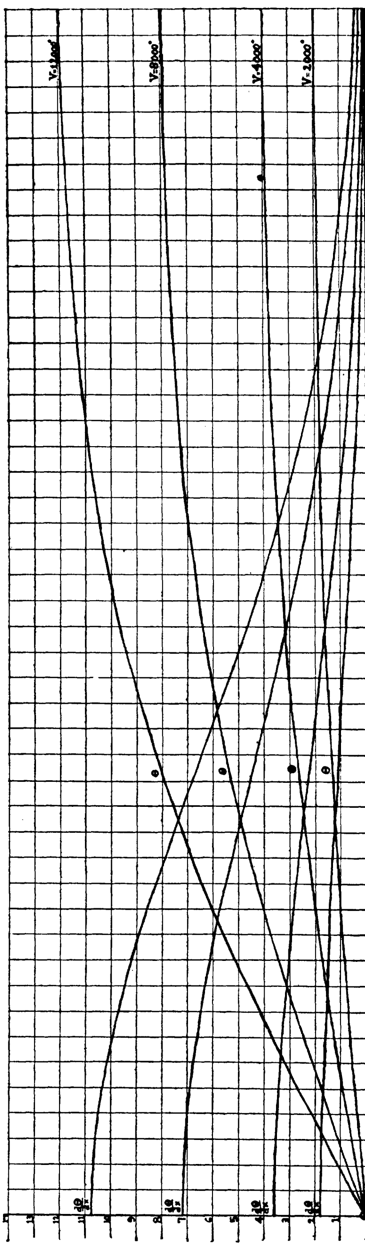

Fig. C. Fourier Solutions for $t=1000$ million years after the initial epoch.

On x-axis 1 unit of Scale = 100 000 feet.

Rate of augmentation of temperature at Surface 1° Fahr. for 51 feet.

the exact path of the temperature curve where it passes through the layers just beneath the crust. The only condition one can be sure of is that it shall be everywhere continuous and have no change of flexure. It is outwardly concave near the surface, and it must remain so till we reach the arch of the ellipse. In the diagram for the earth's temperature we have drawn this curve according to what seemed to be its most probable course.

It is interesting to observe what the effect of this change of temperature near the surface is on the analysis of Lord Kelvin. We have

$$\frac{d\Theta}{dx} = \frac{V}{\sqrt{\pi\kappa t}} e^{-\frac{x^2}{4\kappa t}}.$$

And it appears that if the temperature increases more rapidly as we go downward, V would be larger for given depth, and the gradient near the surface would be steeper. The same effect could be produced by shortening the time t without changing the value of V. We have adopted this course as the most probable in the treatment of the question given above.

Also since

$$V = \frac{(\Theta - \Theta_0)\sqrt{\pi}}{2\int_0^{\frac{x}{2\sqrt{\kappa t}}} e^{-z^2} dz},$$

V would be changed by changing the limits of the integral, or by modifying the value of Θ. But the integral depends only on x and t, and when these do not change appreciably it is most natural to depart from Fourier's solution by change of Θ.

IV. On the Theory of Earthquakes Held by the Ancients.

§ 17. *On the Inaccessibility of the Views of the Greeks.*

Since Science is the outgrowth of successive revolutions of thought in the course of centuries, it is unfortunate that the views of the Greeks and Romans on many questions are not always accessible to modern readers. It is chiefly by a survey of human thought over long periods that one is enabled to form a clear conception of what has been done in a given subject. Too few students of science

have been able to make an adequate examination of the theory of earthquakes held by the Greeks.

The great multiplicity of subjects in our day, with the resulting unfortunate departure of education from the classic standard, has rendered the original languages of the best ancient authors well-nigh unintelligible to many men of science, because good translations are seldom accessible. One not infrequently meets with surprise even on the part of men of eminence and originality that anything valuable should be found in the writings of the Greeks and Romans.

A masterly grasp of the ancient languages on the part of men of science perhaps is not to be expected, but unfamiliarity with the general spirit of Greek thought is a serious inconvenience, because this defect often leaves the investigator without an adequate view of his own subject. There may thus arise a lack of reverence for the learning of the ancients, because their works are not understood. The poems of Homer and Sophocles, the eloquence of Demosthenes and Cicero, the sculptures of Phidias and Praxiteles, the paintings of Polygnotus and Apelles, the medical knowledge of Hippocrates and Galen, the philosophy of Plato and Aristotle, the astronomical researches of Hipparchus and Ptolemy, the mathematical discoveries of Apollonius and Archimedes—these and many other wonders of antiquity are not calculated to excite a contemptible opinion of the achievements of the Greeks. The perfection of their intellectual labors is attested by the great writers of all subsequent ages, and in modern times by none more amply than by Humboldt and Lyell, who did so much for the foundation of geology.

But while there has been some interest in the theories of the ancients, it has seemed of late years to have become more desultory, which must be ascribed chiefly to the inaccessibility of their works. The English reader possesses the well known translations of Bohn's Classical Library, which often have decided merit; but unfortunately they do not include all the works of Aristotle, the foremost physical philosopher among the Greeks, and the greatest thinker of the ancient times. He included his discussion of earthquakes in the treatise on meteorology, which has never been put into an acessible English translation. Taylor's translation lacks in scholarship, and was limited to fifty copies.

Strange as it may seem at first sight, it is owing principally to the wide grasp and characteristic penetration of Aristotle that he correctly put his discussion of earthquakes in the book which treats of the phenomena of the air. For he observed the connection between earthquakes and volcanoes as clearly as any modern man of science could do; and having noticed that in eruptions vapors escape from the earth and diffuse themselves in the atmosphere, he justly concluded that earthquakes are due to the action of pent-up vapors, even when they do not break through and escape to the surface. Could Newton, Laplace, Fourier or any modern investigator reason better than Aristotle has done on this point? In spite of some inevitable errors, due to the early time in which he lived, the penetration which he shows must be indeed a matter of surprise to all thoughtful students of the physics of the earth.

It is obvious that one should not expect from the Greeks and Romans highly finished theories, such as we find in some branches of modern science. If their thought was characterized by general soundness, it may justly excite our wonder. For with all the advantages of the vast learning of our time and the experience of centuries, we cannot claim that the moderns have always been equally fortunate. For example, in speaking of Tycho Brahé, Laplace justly remarks that notwithstanding his great genius for making astronomical observations he had little understanding for physical causes, on which the science of the heavens might be established; and the same remark applies to all except a few of the total number of investigators of subsequent time.

However many working hypothesis may be imagined, it is clear that no real science can be developed until the true physical cause of a phenomenon is discovered. So difficult is the discovery of causes that in speaking of Posidonius, Strabo ("Geog.," Lib. II., Chap. Iv., § 2) says that "he (Posidonius) is much too fond of imitating Aristotle's propensity for diving into *causes,* a subject which we (Stoics) scrupulously avoid, simply because of the extreme darkness in which all *causes* are enveloped." This remark enables one to understand why Aristotle, Posidonius and Archimedes stand so preeminent among the ancients.

Although the Romans had ample political and military instincts,

it is generally recognized that they had very inadequate scientific and philosophic intuition; their philosophers therefore adopted the theories of the Greeks, whose genius they admired. They copied and preserved, but added little to, the treasures of their intellectual masters. Thus Aristotle's explanations are incorporated into the writings of Seneca and Pliny. Aristotle himself gives the history of thought up to his time; and as Strabo was the most important of the later Greek writers on the theory of the world, while Pliny takes the foremost place among corresponding Roman authors, we have in the writings of these three great naturalists a comprehensive digest of the views of antiquity.

Although in his youth Aristotle was trained under Plato, in his later period he composed all his work in a condensed and direct style, without any of the allegorical symbolism so much used by the founder of the Academy. As his death was somewhat premature, at the age of about 63, it is thought by scholars that most all his works were left unfinished. Strabo gives the following account of the vicissitudes of Aristotle's manuscripts:

"The Socratic philosophers, Erastus, Coriscus and Neleus, the son of Coriscus, a disciple of Aristotle, and Theophrastus, were natives of Scepsis. Neleus succeeded to the possession of the library of Theophrastus, which included that of Aristotle; for Aristotle gave his library, and left his school, to Theophrastus. Aristotle was the first person with whom we are acquainted who made a collection of books, and suggested to the kings of Egypt the formation of a library. Theophrastus left his library to Neleus, who carried it to Scepsis, and bequeathed it to some ignorant persons who kept the books locked up, lying in disorder. When the Scepsians understood that the Attalic kings, on whom the city was dependent, were in eager search for books, with which they intended to furnish the library at Pergamus, they hid theirs in an excavation under ground; at length, but not before they had been injured by damp and worms, the descendants of Neleus sold the books of Aristotle and Theophrastus for a large sum of money to Apellicon of Teos. Appellicon was rather a lover of books than a philosopher; when therefore he attempted to restore the parts which had been eaten and corroded by worms, he made alterations in the original text and introduced them into new copies; he moreover supplied the defective parts unskillfully, and published the books full of errors. It was the misfortune of the ancient Peripatetics, those after Theophrastus, that being wholly unprovided with the books of Aristotle, with the exception of a few only, and those chiefly of the exoteric (popular) kind, they were unable to philosophize according to the principles of the system, and merely occupied themselves in elaborate discussions on commonplaces. Their successors, however, from the time

that these books were published, philosophized, and propounded the doctrines of Aristotle more successfully than their predecessors, but were under the necessity of advancing a great deal as probable only, on account of the multitude of errors contained in the copies.

"Even Rome contributed to this increase of errors; for immediately on the death of Apellicon, Sylla, who captured Athens, seized the library of Apellicon. When it was brought to Rome, Tyrannion, the grammarian, who was an admirer of Aristotle, courted the superintendent of the library and obtained the use of it. Some venders of books, also, employed bad scribes and neglected to compare the copies with the original. This happens in the case of other books which are copied for sale both here and at Alexandreia." (Strabo's "Geography," XIII., Cap. 1, § 54; Bohn's Transl., Vol. II., pp. 378–380.)

There are naturally many points in regard to the writings of Aristotle on which scholars are not agreed, but since according to this account the entire works of Aristotle from his own manuscripts were first published at Rome during Strabo's lifetime, the substantial accuracy of the above statement can hardly be questioned. It is gratifying to find that, so far as one can now judge, Aristotle's views on earthquakes do not seem to have suffered any material corruption during the many centuries through which they have been transmitted to us. We may safely infer this from the theory as given by Strabo, soon after the publication of Aristotle's works, and from the theory given by Pliny, who had access to the writings of both Aristotle and Strabo, compared to the original Aristotelian doctrines set forth in the book on "Meteorology," the authenticity of which is unquestioned.

§ 18. *The Theory of Plato.* (*427–347 B. C.*)

As Plato was the teacher of Aristotle, but is not quoted in the account given in the "Meteorology," it seems likely that the expressions in Plato's works may be worthy of notice. The following citations are from Jowett's Translations of Plato's Dialogues.

In the *Phaedo* Plato gives the following discussion between Socrates and Simmias:

"'That,' said Simmias, 'will be enough.'

"'Well, then,' he said, 'my conviction is that the earth is a round body in the center of the heavens, and therefore has no need of air or any similar force as a support, but is kept there and hindered from falling or inclining any way by the equability of the surrounding heaven and by her own equipoise. For that which, being in equipoise, is in the center of that which is

equably diffused, will not incline any way in any degree, but will always remain in the same state and not deviate. And this is my first notion.'

"'Which is surely a correct one,' said Simmias.

"'Also I believe that the earth is very vast, and that we who dwell in the region extending from the river Phasis to the Pillars of Herakles, along the borders of the sea, are just like ants or frogs about a marsh, and inhabit a small portion only, and that many others dwell in many like places. For I should say that in all parts of the earth there are hollows of various forms and sizes, into which the water and the mist and the air collect; and that the true earth is pure and in the pure heaven, in which also are the stars—that is the heaven which is commonly spoken of as the ether, of which this is but the sediment collecting in the hollows of the earth. But we who live in these hollows are deceived into the notion that we are dwelling above on the surface of the earth; which is just as if a creature who was at the bottom of the sea were to fancy that he was on the surface of the water, and that the sea was a heaven through which he saw the sun and the other stars—he having never come to the surface by reason of his feebleness and sluggishness, and having never lifted up his head and seen, nor ever heard from one who had seen, this other region which is so much purer and fairer than his own. Now this is exactly our case: for we are dwelling in a hollow of the earth, and fancy that we are on the surface; and the air we call the heaven, and in this we imagine that the stars move. But this is also owing to our feebleness and sluggishness, which prevent our reaching the surface of the air: for if any man could arrive at the exterior limit, or take the wings of a bird and fly upward, like a fish who puts his head out and sees this world, he would see a world beyond; and, if the nature of man could sustain the sight, he would acknowledge that this was the place of the true heaven and the true light and the true stars. For this earth, and the stones, and the entire region which surrounds us are spoilt and corroded, like the things in the sea which are corroded by the brine; for in the sea too there is hardly any noble or perfect growth, but clefts only, and sand, and an endless slough of mud: and even the shore is not to be compared to the fairer sights of this world. And greater far is the superiority of the other. Now of that upper earth which is under the heaven, I can tell you a charming tale, Simmias, which is well worth hearing.'

"'And we, Socrates,' replied Simmias, 'shall be charmed to listen.'

"'The tale, my friend,' he said, 'is as follows. In the first place, the earth, when looked at from above, is like one of those balls which have leather coverings in twelve pieces, and is of divers colors, of which the colors which painters use on earth are only a sample. But there the whole earth is made up of them, and they are brighter far and clearer than ours; there is a purple of wonderful luster, also the radiance of gold, and the white which is in the earth is whiter than any chalk or snow. Of these and other colors the earth is made up, and they are more in number and fairer than the eye of man has ever seen; and the very hollows (of which I was speaking) filled with air and water are seen like light flashing amid the other colors, and have a color of their own, which gives a sort of unity to the variety of earth. And in this fair region everything that grows—trees, and flowers, and fruits—

is in a like degree fairer than any here; and there are hills, and stones in them in a like degree smoother, and more transparent, and fairer in color than our highly valued emeralds and sardonyxes and jaspers, and other gems, which are but minute fragments of them: for there all the stones are like our precious stones, and fairer still. The reason of this is that they are pure, and not, like our precious stones, infected or corroded by the corrupt briny elements which coagulate among us, and which breed foulness and disease both in earth and stones, as well as in animals and plants. They are the jewels of the upper earth, which also shines with gold and silver and the like, and they are visible to sight and large and abundant and found in every region of the earth, and blessed is he who sees them. And upon the earth are animals and men, some in a middle region, others dwelling about the air as we dwell about the sea; others in islands which the air flows round, near the continent: and in a word, the air is used by them as the water and the sea are by us, and the ether is to them what the air is to us. Moreover, the temperament of their seasons is such that they have no disease, and live much longer than we do, and have sight and hearing and smell, and all the other senses, in far greater perfection, in the same degree that air is purer than water or the ether than air. Also they have temples and sacred places in which the gods really dwell, and they hear their voices and receive their answers, and are conscious of them and hold converse with them, and they see the sun, moon, and stars as they really are, and their other blessedness is of a piece with this.

"'Such is the nature of the whole earth, and of the things which are around the earth; and there are divers regions in the hollows on the face of the globe everywhere, some of them deeper and also wider than that which we inhabit, others deeper and with a narrower opening than ours, and some are shallower and wider; all have numerous perforations, and passages broad and narrow in the interior of the earth, connecting them with one another; and there flows into and out of them, as into basins, a vast tide of water, and huge subterranean streams of perennial rivers, and springs hot and cold, and a great fire, and great rivers of fire, and streams of liquid mud, thin or thick (like the rivers of mud in Sicily, and the lava-streams which follow them), and the regions about which they happen to flow are filled up with them. And there is a sort of swing in the interior of the earth which moves all this up and down. Now the swing is in this wise. There is a chasm which is the vastest of them all, and pierces right through the whole earth; this is that which Homer describes in the words,—

"'Far off, where is the inmost depth beneath the earth'; and which he in other places, and many other poets, have called Tartarus. And the swing is caused by the streams flowing into and out of this chasm, and they each have the nature of the soil through which they flow. And the reason why the streams are always flowing in and out is that the watery element has no bed or bottom, and is surging and swinging up and down, and the surrounding wind and air do the same; they follow the water up and down, hither and thither, over the earth—just as in respiring the air is always in process of inhalation and exhalation; and the wind swinging with the water in and out produces fearful and irresistible blasts: when the waters retire with a

rush into the lower parts of the earth, as they are called, they flow through the earth into those regions, and fill them up as with the alternate motion of a pump, and then when they leave those regions and rush back hither, they again fill the hollows here, and when these are filled, flow through subterranean channels and find their way to their several places, forming seas, and lakes, and rivers, and springs. Thence they again enter the earth, some of them making a long circuit into many lands, others going to few places and those not distant, and again fall into Tartarus, some at a point a good deal lower than that at which they rose, and others not much lower, but all in some degree lower than the point of issue. And some burst forth again on the opposite side, and some on the same side, and some wind round the earth with one or many folds, like the coils of a serpent, and descend as far as they can, but always return and fall into the lake. The rivers on either side can descend only to the center and no further, for to the rivers on both sides the opposite side is a precipice.

"'Now these rivers are many, and mighty, and diverse, and there are four principal ones, of which the greatest and outermost is that called Oceanus, which flows round the earth in a circle; and in the opposite direction flows Acheron, which passes under the earth through desert places, into the Acherusian lake: this is the lake to the shores of which the souls of the many go when they are dead, and after waiting an appointed time, which is to some a longer and to some a shorter time, they are sent back again to be born as animals. The third river rises between the two, and near the place of rising pours into a vast region of fire, and forms a lake larger than the Mediterranean Sea, boiling with water and mud; and proceeding muddy and turbid, and winding about the earth, comes among other places, to the extremities of the Acherusian lake, but mingles not with the waters of the lake, and after making many coils about the earth plunges into Tartarus at a deeper level. This is that Pyriphlegethon, as the stream is called, which throws up jets of fire in all sorts of places. The fourth river goes out on the opposite side, and falls first of all into a wild and savage region, which is all of a dark-blue color, like lapis lazuli; and this is that river which is called the Stygian river, and falls into and forms the lake Styx, and after falling into the lake and receiving strange powers in the waters, passes under the earth, winding round in the opposite direction to Pyriphlegethon, and meeting in the Acherusian lake from the opposite side. And the water of this river too mingles with no other, but flows round in a circle and falls into Tartarus over against Pyriphlegethon; and the name of this river, as the poets say, is Cocytus.'"

In the *Timeus* Plato represents a priest of Sais in Egypt as saying to Solon:

"'There have been and will be again, many destructions of mankind arising out of many causes; the greatest have been brought about by the agencies of fire and water, and other lesser ones by innumerable other causes. There is a story which even you have preserved, that once upon a time Phaethon, the son of Helios, having yoked the steeds of his father's chariot, because he was not able to drive them in the path of his father, burnt up all that was

upon the earth, and was himself destroyed by a thunderbolt. Now this has the form of a myth but really signifies a declination of the bodies moving in the heavens around the earth, and a great conflagration of things upon the earth, which recurs after long intervals; at such times those who live upon the mountains and in dry and lofty places are more liable to destruction than those who dwell by rivers or on the seashore. And from this calamity the Nile, who is our never failing saviour, delivers and preserves us. When on the other hand, the gods purge the earth with a deluge of water, the survivors in your country are herdsmen and shepherds who dwell in the mountains, but those who, like you, live in cities are carried by the rivers into the sea. . . .'"

Plato continues the discourse and finally tells of the sinking of the islands of Atlantis by an earthquake:

"'Many great and wonderful deeds are recorded of your state in our histories. But one of them exceeds all the rest in greatness and valour. For these histories tell of a mighty power which unprovoked made an expedition against the whole of Europe and Asia, and to which your city put an end. This power came forth out of the Atlantic Ocean, for in those days the Atlantic was navigable; and there was an island situated in front of the straits which are by you called the pillars of Herakles; the island was larger than Libya and Asia put together, and was the way to other islands, and from these you might pass to the whole of the opposite continent which surrounds the true ocean; for this sea which is within the Straits of Herakles is only a harbor, having a narrow entrance, but that other is a real sea, and the surrounding land may be most truly called a boundless continent. Now in this island of Atlantis there was a great and wonderful empire which had rule over the whole island and several others, and over parts of the continent, and, furthermore, the men of Atlantis had subjected the parts of Libya within the columns of Herakles as far as Egypt, and of Europe as far as Tyrrhenia. This vast power, gathered into one, endeavored to subdue at a blow our country and yours and the whole of the region within the straits; and then, Solon, your country shone forth, in the excellence of her virtue and strength, among all mankind. She was preeminent in courage and military skill, and was the leader of the Hellenes.

"'And when the rest fell off from her, being compelled to stand alone after having undergone the very extremity of danger, she defeated and triumphed over the invaders, and preserved from slavery those who were not yet subjugated, and generously liberated all the rest of us who dwell within the pillars. But afterwards there occurred violent earthquakes and floods, and in a single day and night of misfortune all your warlike men in a body sank into the earth, and the island of Atlantis in like manner disappeared in the depths of the sea. For which reason the sea in those parts is impassable because there is a shoal of mud in the way; and this was caused by the subsidence of the island.'"

This account clearly shows that Plato ascribed to earthquakes the power to cause the submergence of land beneath the sea. As he was an excellent geologist for his time, he no doubt accepted also

the doctrine of the upheaval of the land by earthquakes. Aristotle distinctly states that these calamities are forgotten and lost from memory by the migrations of peoples and the ravages of time, and Plato clearly holds the same view.

§ 19. *The Theory of Aristotle* (384–322 B. C.).

The English translation given below is based on the Greek Text employed in the Tauchnitz edition of the works of Aristotle. The "Meteorology" is acknowledged to be a genuine production of the Stageirite, and the chief difficulty in translating it consists in the peculiar terminology and terseness of style used in this probably unfinished work. After the present translation was outlined the Rev. Theodore F. Burnham, M.A., very kindly read it and offered a number of valuable suggestions based on his extensive knowledge of Greek. Professor Edward B. Clapp, head of the Department of Greek in the University of California, also favored the translator with valuable criticisms, and very kindly supplied a copy of the scholarly French Translation by Barthelemy Saint-Hilaire, for the purpose of comparison in the final revision. As Aristotle's style is somewhat unique and peculiar to himself, this was felt to be important as a necessary precaution to ensure accuracy, especially where the language of the author is unduly condensed or incomplete, and therefore not easily interpreted.

Aristotle held that the air is produced from the evaporation of water ("Meteor.," Lib. I., Chap. 3) by the fire inside and outside the earth, and says that the air is a kind of vapor. He recognized that air could be heated by rapid and violent motion, and as arranged his adopted system of the world was made up of a lithosphere, a hydrosphere, an atmosphere, a pyrosphere and then beyond all the sphere of ether; certain interchanges took place between these divisions of the world.[1] Aristotle uses separate words for the various

[1] Among the many other points discussed by Aristotle we may mention the following:

1. The primitive fluidity of the globe. He holds, with Thales, that both the earth and sea were originally liquid; that a part was dried up by the sun. Indeed the wise men held that the sea was diminishing in volume by gradual desiccation, but Aristotle does not seem to hold this view. (Lib. II., Cap. 1, § 1–4.)

2. The earth is spherical, not large, fixed in the center of the universe, causes night by its shadow in space, and also eclipses of the moon, the atmosphere being confined to this perishable sublunar sphere, as in the Almagest of Ptolemy, who often follows Aristotle.

phenomena connected with exhalations and vapors; ἡ ἀτμίς for *steam; τό πνεῦμα* for a *blast* of wind or vapor; ἡ ἀναθυμίασις for *exhalation; ὁ ἄνεμος* for *wind.* The translation of πνεῦμα, meaning literally a *breath,* is very difficult, and seems best rendered by the phrase *blast* of wind or vapor, which seems to convey Aristotle's true meaning.

In the "Meteorology," Lib. I., Cap. 4, the following interesting passage occurs:

"It is not true, as they say, that the comet only appears in the north, even at the same time when the sun is in the summer tropic; for indeed the great comet which was seen at the time of the earthquake in Achaia, and the inundation of the sea wave, took its course from the setting of the equinoxes, and several others have been observed towards the south."

Again we read:

"The water which falls in rains drains away and nearly all filters into the earth. But there is in the earth a large amount of fire, and a great heat (ὑπάρχει δ'ἐν τε τῇ γῇ πολὺ πῦρ πολλὴ θερμότης). (Lib. II., Cap. 4.)

Also:

"Thus when it rains, since the earth is dried by the heat which is in it and by that which has escaped above, an exhalation of vapor develops. This is the body of the wind (ἀνέμου σῶμα). And when this secretion is going on the winds blow. But when they cease because the heat, which is always secreted, is borne to the upper regions, the steam (ἡ ἀτμίς) being cooled, condenses and becomes water; and when the clouds are collected in one place, and the surrounding cold penetrates them, water is formed and cools the dry exhalation" (τὴν ξηρὰν ἀναθυμίασιν). (Lib. II., Cap. 4.)

Aristotle's Theory of Earthquakes is as follows ("Meteorology," Lib. II., Cap. vii.):

"After these things (in relation to the winds) it is necessary to speak with reference to an earthquake and movement of the earth; for the cause of the phenomenon is closely connected with this (theory of the winds).

"Up to the present time there are three explanations of these phenomena, from three different authorities: Anaxagoras the Clazomenian, and before him Anaximenes the Milesian have each discussed them, and subsequently to these Democritus the Abderite.

"Now Anaxagoras holds that the ether when generated is naturally borne upward, and falling into the depths of the earth below, and the cavities, shakes it; and the upper parts of the earth in consequence of the rains are pressed together; and freely admitting that by its nature the earth is everywhere equally porous, he holds that the sphere has in its totality both an elevation and a base, the elevation being the part which we happen to inhabit and the base the other part.

"With reference to this subject then perhaps we ought to say nothing,

simply because it is too superficially proved. To understand the elevation and base in such a way that all the bodies which have weight would not at every place be borne to the earth, while the light bodies and the fire tend upward, is indeed most absurd; for this is going contrary to the evidence of our senses, which show us that the horizon of the habitable world, so far as we know it, varies constantly according to the extent which we ourselves change place, the earth being convex and spherical. To say that on account of its mass it remains in the air, and to maintain that the trembling of the earth arises when it is smitten from below upwards in its totality, is not less strange. Moreover, in these considerations, Anaxagoras takes no account of some circumstances which accompany earthquakes; for not all lands, nor all seasons participate in this commotion, by chance and indiscriminately.

"Democritus indeed holds that the matter of the earth is full of water, and receiving much other water from the rain storms, it is moved by this; but this arises more from the inability to hold (the water) in the yawning cavities, which, breaking forth violently, causes the shaking of the earth; and the ground being dry and drawing forth into the empty places water escaping from the reservoirs, gives rise to motion of sudden agitation.

"Anaximenes, on the other hand, holds that when moistened and afterwards dried out the earth is shattered to pieces, and is shaken from the sinking in of fragments of the hills; from which also arises the earthquakes in the dry, and likewise in the wet, seasons; for in droughts, just as is said, the dry ground is cracked open, and the overmoist earth, produced by the absorption of the waters, subsides. If that happens which is agreeable to the theory of Anaximenes one should observe in many places the earth caving in. Yet by what cause the phenomenon arises in certain places, no one opinion carries extreme weight of authority relatively to others; nevertheless such a claim was put forth.

"This explanation supposes necessarily that earthquakes always become less and less powerful, and finally cease to vibrate. That which settles down ought to do so naturally. Consequently if this is impossible, it is very evident that it can not be the true cause of the phenomenon.

"CAP. VIII.

"But since it manifestly is a necessity, that exhalation of vapor should be produced all the time, both from the moisture and from the dryness, as we have said in what precedes, it is likewise necessary that from these antecedents earthquakes should be produced; for in itself the earth is dry, yet on account of the rains, acquires in its interior much moisture; so that having been warmed by the sun, and the internal fire, largely indeed from without, but also largely from within, the blast of vapor is developed; and this blast when it sometimes escapes externally flows in a continuous manner; and likewise sometimes when it escapes within the earth; and then again it is scattered. If then this can not take place otherwise, we must consider what among all these bodies, is the most capable of producing the motion; this is necessarily that which naturally goes fartherest, and is most violent, but especially of this latter nature.

"Now the most violent is of necessity that which moves the most rapidly;

for it communicates violence principally through the rapid speed. But the body which goes fartherest, is that which most easily traverses all things; and it is the lightest body which is able to do this. Consequently since the nature of the air itself is the lightest, it is the blast of wind which most powerfully moves all bodies; for the fire, whenever accompanied by a blast of wind, produces a flame, and it is borne rapidly. Therefore is it neither the water, nor the earth which is the cause of the shaking, but the blast of wind, whenever the evaporation without may have again accumulated within (the earth). Hence in a calm arise the most and the largest earthquakes; for the exhalation being naturally continuous it follows that in general it will develop with the very first agitation of the cause. Consequently either from within the earth all at once, or from without by a violent impulse, the whole body of vapor rushes en mass. But that some earthquakes should be produced, coincident with a dominant blast of wind is not strange; for we sometimes see several winds blowing together; from this circumstance, whenever one strikes the earth more violently than the other while the blast is blowing an earthquake takes place. But these give rise to tremors of inferior magnitude, because their principle and cause are separated.

"Now the larger number and greatest earthquakes occur by night; those of the day about noon; for the calmest time of the day in general is at noon; for the sun then, when of the greatest power, confines the vapors to the earth; and is most powerful about mid-day; and the nights of these days are calmest, on account of the absence of the sun: consequently there arises from within the earth a streaming movement like the ebb of the tides, in a sense contrary to the flow of the sea without; and this phenomenon generally develops about daybreak; it is at this time that the blasts ordinarily commence to blow. If therefore the force of them by chance turns quickly around, as Euripus (does), on account of the mighty tides of the sea, it produces an earthquake.

"Indeed it is about places of this kind that the mightiest of the earthquakes arise, where the sea is boisterous or the land is porous and cavernous. Wherefore they occur also about the Hellespont, and about Achaia, and Sicily, and about the analogous places of Eubœa; for the sea seems to pass through conduits under the earth. Hence also the warm springs around Aidepsus are produced by the same cause. And around the aforesaid places the earthquakes arise chiefly on account of the narrowness of the conduits; for the current of wind, which ordinarily blows from the land, finds itself driven back by the fullness of the sea which in such places becomes violent.

"The localities which have such caverns below thereby retaining much vapor, are most shaken by earthquakes, and in the spring and the end of autumn principally, and they rise both in the rainy and the dry seasons from the same cause; for these are the seasons in which there is most blowing of wind; in fact both summer and winter, the one by the frigidity and the other by the heat, produces calms; the one being exceedingly cold and the other exceedingly dry.

"Moreover in the dry seasons the air is very windy; for the dryness develops precisely when the dry exhalation is more considerable than the humidity; and in the rainy seasons the internal exhalation increases, and as it finds itself intercepted in very narrow places, and violently confined in a

less space because the cavities are full of water, the stream of wind begins to acquire the force for even the compression of its own bulk in this too limited space; and flowing out and striking against the passages the wind produces a violent earthquake; for it is necessary to bear in mind that, just as in our own body, the force of the breath held within produces a trembling and suffocation, so also in the earth the blast of vapor has an analogous effect; and that the shocks of earthquakes are partly of the nature of trembling and partly of suffocation, just as it often comes to pass after urination that a kind of vibration of the body is produced, a trembling with sudden drawing of the breath from without to the interior; thus arise also such phenomena with respect to the earth.

"In order to take proper account of all the influence which the blast of vapor exerts, it is necessary to observe not only what takes place in the air; for one can believe in the power of such things by their magnitude; but also what happens in the bodies of animals; convulsions and spasms are only motions of the breath, and they have such violence that often several persons uniting all their efforts are unable to keep the movements of the afflicted under control. Now it is necessary to bear in mind that the same thing happens also in the earth, since we naturally judge the great by reference to the small.

"Signs of these things, and according to our own observation, have occurred in many places; for the shaking of the earth arising in certain localities does not cease till the agitating wind has escaped freely into the region above the earth like the blast of a hurricane; it is not long ago since this actually happened at Heraclea in Pontus, and formerly at the island of Hiera, which is one of the islands called after Æolus; in this some earth swelled up, and with a loud noise rose in the form of a hill, and having finally broke forth, the mighty urging blast escaped and ejected sparks and ashes, which covered the region about the Lapari islands, spread over the whole land, and extended even to several cities in Italy: and at the present time where this eruption occurred is still evident; and now the development of fire in the earth must be held to have caused this, at the time of the first outbreak, the particles being reduced to the size of the finest dust of the air. Moreover, it is proved that blasts of vapor circulated beneath the earth, and that this occurred at these islands; for whenever the south wind starts to blow, there are first some premonitory signs of it; for places have it from which eruptions occur, because the sea is already agitated far and wide; and it again confines the swelling vapor within the earth, for the simple reason that the sea is spread over it.

"Accordingly it makes a noise without an earthquake, throughout the open spaces of these regions (imagined as deep conduits), either because the places are very vast, since above the earth they expend into immensity, or because the quantity of air expelled is very small.

"Moreover, the changes of the sun, which grows faint and dark without clouds, and the stillness and extreme cold, which sometimes precede the earthquakes occurring at daybreak are only additional signs of the aforesaid cause; for the sun must be obscured and darkened when the blast of vapor begins to sink within the earth, for dissolving and expelling the air,

and the winds must cease before dawn, and at daybreak, when the cold causes a stillness; for necessarily the stillness in most cases comes to pass, just as was also said before, because it is a reflex of the blast going within the earth, and happens especially before the greatest earthquakes; the blast of vapor is not much scattered, either that without or that within the earth, but borne along its course becomes at daybreak necessarily most violent.

"The cold comes to pass on account of the exhalation of the vapor circulating within, with all the heat naturally contained in it. If the winds do not seem to be warm it is because they move the air filled with cold vapor and considerable steam, just as in the case of the breath exhaled from the mouth; in fact this vapor is but slightly warm, as when we breathe; yet on account of the small amount of the air, the heat of it is not so evident; but further away the breath is cold from the same cause that the winds are.

"From the time that this force enters within the earth, the flowing away of the vapor combined with the moisture makes the cold, in places where this phenomenon is encountered. This is also the cause which ordinarily makes a sign before earthquakes; for whether by day, or a little after sunset, when the sky is clear, a faint cloud appears spreading and lengthening itself out, as a fine line perfectly straight, the blast of wind quieting down on account of the setting (of the sun). Whence similar phenomena come to pass also in the sea, about the shores; and especially whenever it is thrown into billowy waves, exceedingly violent and irregular, breakers at the beach are produced; but whenever a calm arises, because the breaking of the surface is very slight, the waves are small and regular.

"Accordingly that which the sea does around the land, the wind does about the dark clouds of vapor in the air. So that whenever the wind calms down, the cloud which remains is exactly a straight line and very tenuous, as if it were a mere wave of diffuse air.

"On account of these things therefore an earthquake is sometimes produced during the eclipses of the moon; for whenever the closing up of the earth between the sun and moon is near at hand, and the light is not yet indeed altogether gone, and the heat from the sun is still in the air, but already languishing, a calm arises by the wind suddenly whirling about and throwing itself in the earth, which produces the earthquake before eclipses; for the winds often arise before eclipses, winds at nightfall before eclipses at midnight, and winds at midnight before those at dawn. And this comes to pass on account of extinguishing the heat from the moon, whenever the event is already near; in which development the eclipse consists. That which holds the air and calms it having disappeared, it is agitated anew, and a blast of wind arises late in the evening previous to the eclipse.

"But whenever a powerful earthquake occurs it neither ceases immediately nor with a single disturbance; but sometimes it shakes for about forty days; upwards of one and even two years is indicated at certain places. The cause of the violence is the greatness and fullness of the blast of vapor, and the forms of the places from which it flows; that which it strikes against, but does not easily penetrate, shakes most; and it necessarily agitates in the narrow places, just as in the case of obstructed water which is not able to pass through. Wherefore just as in the body the inflamed throbbings do

not cease of a sudden, nor rapidly, but by gradual giving away, along with the decrease of the symptom, so likewise the cause that produces the exhalation of vapor, and the first shock of the blast, do not at once set free the matter, from which are developed the kind of wind, which we call an earthquake. Until therefore the rest of these vapors has escaped the shaking of the earth necessarily continues. But it acts more and more feebly, till the time when the exhalation is too reduced to make a movement which remains sensible.

"And the blast of vapor also makes those sounds which arise beneath the earth, and those which precede earthquakes. And even without earthquakes there are places where these noises are developed under the earth; for just as the air when struck and rent produces all kinds of noises, so likewise also the ground itself produces noises when shaken; for there is no difference, since in the shock everything which agitates is itself shaken in its entirety. The roaring precedes the commotion, because the sound has parts as tenuous as the wind itself, and it penetrates as easily through all bodies.

"And whenever it is unable to move the earth on account of its very lightness, it is certain, since it passes through without difficulty, that it does not make it tremble, but according as it strikes against hard substances with cavities, and all manner of shapes, so they give off all kinds of sounds; consequently it sometimes seems, just as the marvel-mongers say, that the earth is made to roar.

"Occasionally as the result of earthquakes water gushes forth from the ground; but one is not able to say on this account that it was the water which caused the commotion; on the contrary it is always the blast of wind, whether from the surface, or confined below the earth, that produces the violence; and this is the moving power, just as one may say that the winds develop waves in the sea but the waves are not the cause of the winds; and thus then one may say that this earth itself is the cause of the phenomenon; for having been shaken it oscillates, just as water does, for the wave is a kind of oscillation; but the cause of the phenomenon is the same in both (the water and the earth); it experiences the agitation, yet does not produce it; but the blast of vapor is the real cause.

"Wherever along with an earthquake an inundation is produced the cause of it is the development of blasts of wind of a contrary nature. This happens whenever the blast of wind which shakes the earth is unable to repel completely the sea, which another blast of wind controls, nevertheless meeting it, opposing it, and confining it, gathering much force at the same point; for then necessarily the blast of wind confined in the earth by the sea cannot be resisted from breaking open a passage against the force of the opposite blast, and making a cataclysm.

"This is exactly what happened in the region of Achaia; for above the earth there was the south wind on one side, the north wind on the other. A calm having arisen, and the wind flowing within, there was produced at the same time an inundation and the accompanying earthquake; and the violence arose chiefly because the sea would not give passage to the wind imprisoned under the earth, but on the contrary obstructed it. Then having forced open other passages, the blast of vapor produced the earthquake, and the rising of the great sea wave caused the cataclysm.

"On the other hand earthquakes are produced, and often extend over but a small area; yet the winds are not local in character; on the contrary they arise whenever the exhalations, those over the area itself, and those of the neighbouring region, act in concert; just as we say the droughts are produced, and the rainy seasons in turn at any given place. And the earthquakes are produced likewise in the very same manner; but it is not so for the winds, for all these phenomena (the earthquakes, droughts and rains) have their origin in the earth, in such a way that they work together; the power of the sun, however, is not similar, but is rather exerted upon those exhalations high above the earth, so that whenever they experience the influence of the sun's annual circuit, according to the differences of the places on the earth, they all flow together.

"Whenever there is therefore considerable exhalation it shakes the earth, as in a trembling to and fro; it occurs more rarely, and only in certain places, as a pulsation, oscillating up and down; wherefore also shocks of this kind are of slight intensity; for it is not easy for a body of the elements to join together in this movement; since the secretion of vapor is many times larger at the surface than at great depths. Wherever such an earthquake arises, there is a hurling forth of a multitude of stones, just as in the case of sand winnowed by the wind. In this manner, when such an earthquake occurred, ejection of stones took place in Sicily, in the region called the Phlegræan fields, and in the Ligurian country.

"And in the islands of the deep sea earthquakes occur less often than in the islands near the continents. The immensity of the sea cools the exhalations, and it hinders them and resists them by the weight which it imposes upon them. Moreover even when the winds blow the sea always oscillates, and is not shaken powerfully by the agitating blasts.

"But on account of the enormous space it occupies it is not in it, but from it that the exhalations are produced, and those from the earth follow them: and the islands lying close to the mainland are only a part of the mainland itself; the space between, on account of its smallness, being of no importance; but those islands in the sea cannot be moved without disturbng the whole sea, which is spread around them. So much therefore may be said in regard to earthquakes, and their nature, and the cause through which they arise, and the other most important circumstances closely associated with them."

De Mundo,[1] Cap. IV.

(Scholars do not consider this work a genuine production of Aristotle, but no doubt it represents the Peripatetic School of Philosophy.)

"A blast of vapor erupting from the earth is carried upwards from the depths below or from the yawning fissure; whenever it is borne with much whirling movement there is a terrestrial thunderstorm; the blast of vapor ascends to the clouds, dense and moist, and outwardly scatters violently the

[1] περὶ κόσμου πρὸς 'Αλέξανδρον. This must not be confused with the treatise on the heavens, which is entitled περὶ οὐρανου.

collected mass of the cloud, and gives rise to a great noise and clashing, called thunder, just as in water (when heated) a blast of steam breaks forth violently. During the outbreak from the cloud the blast becomes fiery and brilliant, and is called lightning; it strikes before the thunder because it develops before it. . . .

"Now just as the earth includes within it a large amount of water, so likewise it contains also blasts of vapor, and streams of fire. And of these, those which are beneath the earth are obviously invisible; but many have vents, and eruptions, just as Lapari and Aetna and places in the islands of Æolus; which indeed often produce flows as in rivers and belch forth red hot streams of fire; some coming from beneath the earth, near springs of water, heat them, while others arise from springs of lukewarm character; the former being extremely hot, the latter agreeably tempered."

"And similarly many blasts of vapor break out from cavities everywhere in the earth; some of these communicate great enthusiasm to those who approach them, while others cause a languishing effect; and again others are made to sing oracles, as those in Delphi, and in Lebadia, and finally there are some which wholly destroy one another, just as those in Phrygia.

"And quite often also a blast of vapor conveniently tempered in the earth issues forth into its innermost passages, making strange sounds from familar places, and a large part of the blast flows out. Very often also a strong blast of vapor arises from without, and is absorbed in the cavities of the earth, shutting off the escape, and with force shaking it, seeking to break open its own orifice, and producing the phenomena which we are accustomed to call an earthquake.

"And of earthquakes there are some which shake sidewise, at acute angles (obliquely), called *epiclintae;* those shaking upward and downward, at right angles, *brastae,* those in which the ground collapses, making hollows, *chasmatiae,* those opening chasms and breaking the ground all to pieces, called *rhectae.* And of all these, there are some which permit the escape of a blast of vapor; others which throw up stones; others which eject earth, some which disclose sources not suspected before; and still others returning to equilibrium after a single shock, which they call *ostae;* those which rebound, the disturbed body oscillating to and fro, so as always to restore the equilibrium, such shaking is called *palmatiæ,* which produces a phenomenon like a trembling.

"There arises also earthquakes with subterranean thunder, shaking the earth with a roaring noise. Very often apart from an earthquake there arises a roaring of the earth, whenever the vapor is not strong enough to shake it, but nevertheless circulates within, endowed with a powerful rotatory motion.

"There are likewise blasts of vapor which enter the earth's interior, and are absorbed by the waters hidden within the earth. These phenomena are analogous to those which occur in the sea; for there are also chasms where the sea opens out and again when it withdraws, and there is an inundation of waves, and they have a recoil; and occasionally there is only a single pushing away of the sea (πρόωσις), just as is related indeed of Helike and of Boura.

"Frequently there is also produced an eruption of fire from the sea, and a spouting up of springs, and a breaking forth of rivers, and an uprooting of trees, terrible eddies and whirlpools, analogous to those due to blasts of wind; some of these phenomena occur on the depths of the sea, others in Euripus and the straits near the land.

"Many ebbs and flows of waves are said to run in always with the moon, at certain well determined epochs. To speak of the whole in a few words, we may therefore say that the elements mixing together among themselves, in the air, the earth and the sea, there is only considerable probability of the similar properties combining together, bringing to diverse creatures death or life partially, but on the whole conserving the indestructible universe just as it is uncreated. . . .

"In reality terrible earthquakes have thrown in confusion many parts of the earth; the rains suddenly falling produce floods, and ominous outbreaks; inundations of waves, and recessions of the water makes sea where it was land and land where it was sea; the force of the winds and typhoons, are such as to overturn whole cities; volcanoes indeed and flames have broken out, which coming as of old from the heavens, just as they say since the time of Phaethon (driver of the sun's chariot), have burned up the parts towards the dawn; but on the other hand towards hesperus, they issue forth and radiate from the earth, just as the craters which have sent forth the flames of Ætna, and spreading over the ground are carried down as a torrent.

"It is in the terrible catastrophes arising from such an outpouring that the Diety has conspicuously honored the race of the pious who permit themselves to be surrounded by fiery streams of lava, when they take upon their shoulders their aged parents and save them; for when it nears them, the stream of fire, having developed as a river, divides, turning aside here, and again there, and spares the young persons along with their parents, without harming them. And in general, what the pilot is to the ship, the driver to the chariot, the leader to the choir, the law in the state, the general in the army, this the Diety is in the Cosmos."

§ 20. *The Theory of Strabo* (66 B. C.–24 A. D.).

The translation of Strabo's Geography included in Bohn's Library is acknowledged to be good; we shall therefore quote from it some extracts which exhibit Strabo's views. In the introduction to Strabo's "Geography" (Chap. III., § 3–4), this interesting passage occurs:

"Again, having discoursed on the advance of knowledge respecting the geography of the inhabited earth, between the time of Alexander and the period when he was writing, Eratosthenes goes into a description of the figure of the earth; not merely of the habitable earth, an account of which would have been very suitable, but of the whole earth, which should certainly have been given too, but not in this disorderly manner. He proceeds to tell us that the earth is spheroidal, not however perfectly so, inasmuch as it has certain irregularities, then enlarges on the successive changes of form, occasioned by water, fire, earthquakes, eruptions, and the like; all of which

is entirely out of place, for the spheroidal form of the whole earth is the result of the system of the universe, and the phenomenon which he mentions do not in the least change its general form; such little matters being entirely lost in the great mass of the earth. Still they cause various peculiarities in different parts of our globe, and result from a variety of causes.

"He points out as a most interesting subject for disquisition the fact of our finding, often quite inland, two or three thousand stadia from the sea, vast numbers of muscle, oyster, and scallop-shells, and salt-water lakes. He gives as an instance, that about the temple of Ammon, and along the road to it for the space of 3,000 stadia, there are yet found a vast amount of oyster shells, many salt-beds, and salt springs bubbling up, besides which are pointed out numerous fragments of wreck which they say have been cast up through some opening, and dolphins placed on pedestals with the inscriptions, Of the delegates from Cyrene. Herein he agrees with the opinion of Strato the natural philosopher, and Xanthus of Lydia. Xanthus mentioned that in the reign of Ataxerxes there was so great a drought, that every river, lake, and well was dried up: and that in many places he had seen a long way from the sea fossil shells, some like cockles, others resembling scallop shells, also salt lakes in Armenia, Matiana and Lower Phrygia, which induced him to believe that the sea had formerly been where the land now was. Strato, who went more deeply into the cause of these phenomena, was of opinion that formerly there was no exit to the Euxine as now at Byzantium, but that the rivers running into it had forced a way through, and thus let the waters escape into the Propontis, and thence to the Hellespont. And that a like change had occurred in the Mediterranean. For the sea being overflowed by the rivers, had opened for itself a passage by the Pillars of Hercules, and thus, much that was formerly covered by water, had been left dry. He gives as the cause of this, that anciently the levels of the Mediterranean and Atlantic were not the same,. and states that a bank of earth, the remains of the ancient separation of the two seas, is still stretched under water from Europe to Africa. He adds, that the Euxine is the most shallow, and the seas of Crete, Sicily and Sardinia much deeper, which is occasioned by the number of large rivers flowing into the Euxine both from the north and east, and so filling it up with mud, whilst the others preserve their depth. This is the cause of the remarkable sweetness of the Euxine Sea, and of the currents which regularly set towards the deepest part. He gives it as his opinion, that should the rivers continue to flow in the same direction, the Euxine will in time be filled up (by the deposits), since already the left side of the sea is little else than shallows, as also Salmydessus, and the shoals at the mouth of the Ister, and the desert of Scythia, which sailors call the Breasts. Probably too the temple of Ammon was originally close to the sea, though now, by the continual deposit of the waters, it is quite inland: and he conjectures that it was owing to its being so near the sea that it became so celebrated and illustrious, and that it never would have enjoyed the credit it now possesses had it always been equally remote from the sea. Egypt too (he says) was formerly covered by sea as far as the marshes near Pelusium, Mount Casius, and the Lake Sirbonis. Even at the present time, when salt is being dug in Egypt, the beds are found under layers of sand and mingled

with fossil shells, as if this whole district had formerly been under water, and as if the whole region about Casium and Gerrha had been shallows reaching to the Arabian Gulf. The sea afterwards receding left the land uncovered, and the Lake Sirbonis remained, which having afterwards forced itself a passage, became a marsh. In like manner the borders of the Lake Mœris resemble a sea-beach rather than the banks of a river. Every one will admit that formerly at various periods a great portion of the mainland has been covered and again left bare by the sea. Likewise that the land now covered by the sea is not all on the same level, any more than that whereon we dwell, which is now uncovered and has experienced so many changes, as Eratosthenes has observed. Consequently in the reasoning of Xanthus there does not appear to be anything out of place.

"In regard to Strato, however, we must remark that, leaving out of the question the many arguments he has properly stated, some of those which he has brought forward are quite inadmissible. For first he is inaccurate in stating that the beds of the interior and the exterior seas have not the same level, and that the depth of the two seas is different; whereas the cause why the sea is at one time raised, at another depressed, that it inundates certain places and again retreats, is not that the beds have different levels, some higher and some lower, but simply this, that the same beds are at one time raised, at another depressed, causing the sea to rise or subside with them; for having risen they cause an inundation, and when they subside the waters return to their former places. For if it is so, an inundation will of course accompany every sudden increase of the waters of the sea, (as in the spring tides) or the periodical swelling of rivers, in the one instance the waters being brought together from distant parts of the ocean, in the other, their volume being increased. But the rising of the rivers are not violent and sudden, nor do the tides continue any length of time, nor occur irregularly; nor yet along the coast of our sea do they cause inundations nor anywhere else. Consequently we must seek for an explanation of the cause either in the stratum composing the bed of the sea, or in that which is overflowed; we prefer to look for it in the former, since by reason of its humidity it is more liable to shiftings and sudden changes of position, and we shall find that in these matters the wind is the great agent after all. But, I repeat it, the immediate cause of these phenomena, is not in the fact of one part of the bed of the ocean being higher or lower than another, but in the upheaving or depression of the strata on which the waters rest. Strato's hypothesis evidently originated in the belief that that which occurs in rivers is also the case in regard to the sea; viz. that there is a flow of water from the higher places."

Again in Chap. III., section 10:

"Some, however, may be disinclined to admit this explanation, and would rather have proof from things more manifest to the senses, and which seem to meet us at every turn. Now deluges, earthquakes, eruptions of wind, and risings in the bed of the sea, these things cause the rising of the ocean, as sinking of the bottom causes it to become lower. It is not the case that small volcanic or other islands can be raised up from the sea, and not large

ones, nor that all islands can, but not continents, since extensive sinkings of the land no less than small ones have been known; witness the yawning of those chasms which have engulfed whole districts no less than their cities, as is said to have happened to Bura, Bizone, and many other towns at the time of earthquakes: and there is no more reason why one should rather think Sicily to have been disjoined from the mainland of Italy than cast up from the bottom of the sea by the fires of Aetna, as the Lipari and Pithecussan Isles have been."

In Chap. III., sections 16 and 17, we read:

"In order to lessen surprise at such changes as we have mentioned as causes of the inundations and other similar phenomena which are supposed to have produced Sicily, the islands of Aeolus and the Pithecussae, it may be as well to compare with these others of a similar nature, which either now are, or else have been observed in other localities. A large array of such facts placed at once before the eye would serve to allay our astonishment; while that which is uncommon startles our perception, and manifests our general ignorance of the occurrence which takes place in nature and physical existence. For instance, supposing any one should narrate the circumstances concerning Thera and the Therasian Islands, situated in the strait between Crete and the Cyrenaic, Thera being itself the metropolis of Cyrene; or those (in connexion with) Egypt, and many parts of Greece. For midway between Thera and Therasia flames rushed forth from the sea for the space of four days; causing the whole of it to boil and be all on fire; and after a little an island twelve stadia in circumference, composed of the burning mass, was thrown up, as if raised by machinery. After the cessation of this phenomenon, the Rhodians, then masters of the sea, were the first who dared to sail to the place, and they built there on the island a temple to the Asphalian Neptune. Posidonius remarks, that during an earthquake which occurred in Phoenicia, a city situated above Sidon was swallowed up, and that nearly two thirds of Sidon also fell, but not suddenly, and therefore with no great loss of life. That the same occurred, though in a lighter form, throughout nearly the whole of Syria, and was felt even in some of the Cyclades and the Island of Euboea, so that the fountains of Arethusa, a spring in Chalcis, were completely obstructed, and after some time forced for themselves another opening, and the whole island ceased not to experience shocks until a chasm was rent open in the earth in the plain of Lelanto, from which poured a river of burning mud.

"17. Many writers have recorded similar occurrences, but it will suffice to narrate those which have been collected by Demetrius of Skepsis.

"Apropos of that passage of Homer:

"'And now they reach'd the running rivulets clear,
Where from Scamandar's dizzy flood arise
Two fountains, tepid one, from which a smoke
Issues voluminous as from a fire,
The other, even in summer heats, like hail
For cold, or snow, or crystal stream frost-bound:'"

"this writer tells us we must not be surprised, that although the cold spring still remains, the hot cannot be discovered; and says we must reckon the failing of the hot spring as the cause. He goes on to relate certain catastrophes recorded by Democles, how formerly in the reign of Tantalus there were great earthquakes in Lydia and Ionia as far as the Troad, which swallowed up whole villages and overturned Mount Sipylus; marshes then became lakes, and the city of Troy was covered by the waters. Pharos, near Egypt, which anciently was an island, may now be called a peninsula, and the same may be said of Tyre and Clazomenæ."

In Chap. III., section 18:

"Of Bura and Helice, one has been swallowed by an earthquake, the other covered by the waves. Near to Methone, which is on the Hermionic Gulf, a mountain seven stadia in height was cast up during a fiery eruption; during the day it could not be approached on account of the heat and sulphureous smell; at night it emitted an agreeable odour, appeared brilliant at a distance, and was so hot that the sea boiled around it to a distance of five stadia, and appeared in a state of agitation for twenty stadia, the heap being formed of fragments of rock as large as towers."

In Chap. III., sections 19–21, we find this account:

"Duris informs us that the Rhagæ in Media gained that appellation from chasms made in the ground near the Gates of the Caspian by earthquakes, in which many cities and villages were destroyed, and the rivers underwent various changes. Ion, in his satirical composition of Omphale, has said of Eubœa,

"'The light wave of the Euripus has divided the land of Eubœa from Bœotia, separating the projecting land by a strait.'

"20. Demetrius of Callatis, speaking of the earthquakes which formerly occurred throughout the whole of Greece, states that a great portion of the Lichadian Islands and of Kenæum were submerged; that the hot springs of Ædepsus and Thermopylæ were suppressed for three days, and that when they commenced to run again those of Ædepsus gushed from new fountains. That at Oreus on the sea coast the wall and nearly seven hundred houses fell at once. That the greater part of Echinus, Phalara, and Heraclæa of Trachis were thrown down, Phalara being overturned from its very foundations. That almost the same misfortune occurred to the Lamians and inhabitants of Larissa; that Scarpheia was overthrown from its foundations, not less than one thousand seven hundred persons being swallowed up, and at Thronium more than half that number. That a torrent of water gushed forth taking three directions, one to Scarphe and Thronium, another to Thermopylæ, and a third to the plains of Daphnus in Phocis. That the springs of (many) rivers were for several days dried up; that the course of the Sperchius was changed, thus rendering navigable what formerly was highways; that the Boagrius flowed through another channel; that many parts of Alope, Cynus and Opus were injured, and the castle of Œum, which commands the latter city, entirely overturned. That part of the wall of Elateia was thrown down; and that at Alponus, during the celebration of the

games in honour of Ceres, twenty-five maidens, who had mounted a tower to enjoy the show exhibited in the port, were precipitated into the sea by the falling of the tower. They also record that a large fissure was made (by the water) through the midst of the island of Atalanta, opposite Eubœa, sufficient for ships to sail in; that the course of the channel was in places as broad as twenty stadia between the plains; and that a trireme being raised (thereby) out of the docks, was carried over the walls."

Strabo's description of Vesuvius is of interest:

"Above these places is Mount Vesuvius, which is covered with very beautiful fields, excepting its summit, a great part of which is level, but wholly sterile. It appears ash-coloured to the eye, cavernous hollows appear formed of blackened stones, looking as if they had been subjected to the action of fire. From this we may infer that the place was formerly in a burning state with live craters, which however became extinguished on the failing of the fuel. Perhaps this (volcano) may have been the cause of the fertility of the surrounding country, the same as occurs in Catana, where they say that that portion which has been covered with ashes thrown up by the fires of Ætna is most excellent for the vine." (Lib. V., Cap. 4, § 8; p. 367 in vol. I of Bohn's Transl.).

Again in Lib. V., Cap. 4, § 9, he continues;

"In front of Misenum lies the island of Prochyta, which has been rent from the Pithecussæ. Pithecussæ was peopled by a colony of Eretrians and Chalcidians, which was very prosperous on account of the fertility of the soil and the productive gold-mines; however, they abandoned the island on account of civil dissensions, and were ultimately driven out by earthquakes, and eruptions of fire, sea, and hot waters. It was on account of these eruptions, to which the island is subject, that the colonists sent by Hiero, the king of Syracuse, abandoned the island, together with the town which they had built, when it was taken possession of by the Neapolitans. This explains the myth concerning Typhon, who, they say, lies beneath the island, and when he turns himself, causes flames and water to rush forth, and sometimes even small islands to rise in the sea, containing springs of hot water. Pindar throws more credibility into the myth, by making it conformable to the actual phenomena, for the whole strait from Cumaea to Sicily is subigneous, and below the sea has certain galleries which form a communication between (the volcanoes of the island) and those of the main-land. He shows that Aetna is on this account of the nature described by all, and also the Lipari Islands, with the regions around Dicæarchia, Neapolis, Baiae, and the Pithecussæ. And mindful hereof, (Pindar) says that Typhon lies under the whole of the space.

"'Now indeed the sea-girt shores beyond Cumæ, and Sicily, press on his shaggy breast.'

"Timæus, who remarks that many paradoxical accounts were related by the ancients concerning the Pithecussæ, states, nevertheless, that a little before his time, Mount Epomeus, in the middle of the island, being shaken by an earthquake, vomited forth fire; and that the land between it and the coast was driven out into the sea. The powdered soil, after being whirled

high, was poured down again upon the island in a whirlwind. That the sea retired from it to a distance of three stadia, but after remaining so for a short time it returned, and inundated the island, thus extinguishing the fire. And the inhabitants of the continent fled at the noise, from the sea-coast, into the interior of Campania."

The following passage about the town of the Rhegini gives Strabo's views of volcanoes as safety valves (Lib. VI., Cap. I, § 6, pp. 386–387):

"It was called Rhegium either, as Aeschylus says, because of the convulsions which had taken place in this region; for Sicily was broken from the continent by earthquakes,

"'Whence it is called Rhegium.'

Others, as well as he, have affirmed the same thing, and adduce as an evidence that which is observed about Ætna, and the appearances seen in other parts of Sicily, the Lipari and neighbouring islands, and even in the Pithecussæ, with the whole coast beyond them, which prove that it was not unlikely that this convulsion had taken place. But now these mouths being opened, through which fire is drawn up, and the ardent masses and water poured out, they say that the land in the neighbourhood of the Strait of Sicily rarely suffers from the effects of earthquakes; but formerly all the passages to the surface being blocked up, the fire which was smouldering beneath the earth, together with the vapour, occasioned terrible earthquakes, and the regions, being disturbed by the force of the pent up winds, sometimes gave way, and being rent received the sea, which flowed in from either side; and thus were formed both this strait and the sea which surrounds the other islands in the neighbourhood. For Prochyta and the Pithecussæ, as well as Capreæ, Leucosia, the Sirenes, and the Œnotrides, are but so many detached fragments from the continent, but other islands have risen from the bottom of the sea, a circumstance which frequently occurs in many places; for it is more reasonable to think that the islands in the midst of the sea have been raised up from the bottom, and that those which lie off headlands and are separated merely by a strait were broken off from them."

In describing Mount Aetna he says (Lib. VI., Cap. 2, § 8–9; pp. 414–415):

"Near to Centoripa is the town we have a little before mentioned, Ætna, which serves as a place for travelers about to ascend Mount Ætna, to halt and refresh themselves for the expedition. For here commences the region in which is situated the summit of the mountain. The districts above are barren and covered with ashes, which are surmounted by the snows in winter; all below it however is filled with woods and plantations of all kinds. It seems that the summits of the mountain take many changes by the ravages of the fire, which sometimes is brought into one crater, and at another is divided; at one time again it heaves forth streams of lava, and at another flames and thick smoke: at other times again ejecting red-hot masses of fire-stone. In such violent commotions as these the subterranean passages

must necessarily undergo a corresponding change, and at times the orifices on the surface around be considerably increased. Some who have very recently ascended the mountain, reported to us, that they found at the top an even plain of about 20 stadia in circumference, enclosed by an overhanging ridge of ashes about the height of a wall, so that those who are desirous of proceeding further are obliged to leap down into the plain. They noticed in the midst of it a mound; it was ash-coloured, as was likewise the plain in appearance. Above the mound a column of cloud reared itself in a perpendicular line to the height of 200 stadia, and remained motionless (there being no air stirring at the time); it resembled smoke. Two of the party resolutely attempted to proceed further across this plain, but, finding the sand very hot and sinking very deep in it, they turned back, without however being able to make any more particular observations, as to what we have described, than those who beheld from a greater distance. They were, however, of opinion, from the observations they were able to make, that much exaggeration pervades the accounts we have of the volcano, and especially the tale about Empedocles, that he leaped into the crater, and left as a vestige of his folly one of the brazen sandals which he wore, it being found outside at a short distance from the lip of the crater, with the appearance of having been cast up by the violence of the flame; for neither is the place approachable nor even visible, nor yet was it likely that anything could be cast in thither, on account of the contrary currents of vapours and other matters cast up from the lower parts of the mountain, and also on account of the overpowering excess of heat, which would most likely meet any one before approaching the mouth of the crater; and if eventually any thing should be cast down, it would be totally decomposed before it were cast up again, what manner of form soever it might have had at first. And again, although it is not unreasonable to suppose that the force of the vapour and fire is occasionally slackened for want of a continual supply of fuel, still we are not to conclude that it is ever possible for a man to approach it in the presence of so great an opposing power. Ætna more especially commands the shore along the Strait and Catana, but it also overlooks the sea that washes Tyrrhenia and the Lipari Islands. By night a glowing light appears on its summit, but in the day-time it is enveloped with smoke and thick darkness.

"The Nebrodes mountains take their rise opposite to Ætna; they are not so lofty as Ætna, but extend over a much greater surface. The whole island is hollow under ground, and full of rivers and fire like the bed of the Tyrrhenian Sea, as far as Cumæa, as we before described. For there are hot springs in many places in the island, some of which are saline, as those named Selinuntia and the springs at Himera, while those at Ægesta are fresh."

Again (Lib. VI., cap. 2, § 10; pp. 417–418) Strabo says:

"Phænomena, similar to these, and such as take place throughout Sicily, are witnessed in the Lipari Islands, and especially in Lipari itself. These islands are seven in number, the chief of which is Lipari, a colony of the Cnidians. It was nearest to Sicily after Thermessa. It was originally named

Meligunis. It was possessed of a fleet, and for a considerable time repelled the incursions of the Tyrrheni. The islands now called Liparæan were subject to it, some call them the islands of Æolus. The citizens were so successful as to make frequent offerings of the spoils taken in war to the temple of Apollo at Delphi. It possesses a fertile soil, and mines of alum easy to be wrought, hot springs, and craters. (Thermessa) is, as it were, situated between this and Sicily; it is now designated as Hiera, or sacred to Vulcan; it is entirely rocky, and desert, and volcanic. In it are three craters, and the flames which issue from the largest are accompanied with burning masses of lava, which have already obstructed a considerable portion of the strait (between Thermessa and the island Lipari); repeated observations have led to the belief that the flames of the volcanoes, both in this island and at Mont Ætna, are stimulated by the winds as they rise; and when the winds are lulled, the flames also subside; nor is this without reason, for if the winds are both originally produced and kept up by the vapours arising from the sea, those who witness these phenomena will not be surprised, if the fire should be excited in some such way, by the like aliment and circumstances. Polybius tells us that one of the three craters of the island has partly fallen down, while the larger of the two that remain has a lip, the circumference of which is five stadia, and the diameter nearly fifty feet, and its elevation about a stadium from the level of the sea, whch may be seen at the base in calm weather; but if we are to credit this, we may as well attend to what has been reported concerning Empedocles. (Polybius) also says, that when the south wind is to blow, a thick cloud lies stretched round the island, so that one cannot see even as far as Sicily in the distance; but when there is to be a north wind, the clear flames ascend to a great height above the said crater, and great rumblings are heard; while for the west wind effects are produced about half way between these two. The other craters are similarly affected, but their exhalations are not so violent. Indeed, it is possible to foretell what wind will blow three days beforehand, from the degree of intensity of the rumbling, and also from the part whence the exhalations, flames, and smoky blazes issue."

Strabo describes the Aeloian Islands, and includes this account of one of them (Lib. VI., cap. 2, § 11; pp. 420–421):

"The seventh (island) is called Euonymus; it is the fartherest in the sea and barren. It is called Euonymus because it lies the most to the left when you sail from the island of Lipari to Sicily, and many times flames of fire have been seen to rise to the surface, and play upon the sea round the islands: these flames rush with violence from the cavities at the bottom of the sea, and force for themselves a passage to the open air. Posodinius says, that at a time so recent as to be almost within his recollection, about the summer solstice and at break of day, between Hiera and Euonymus, the sea was observed to be suddenly raised aloft, and to abide sometime raised in a compact mass and then to subside. Some ventured to approach that part in their ships; they observed the dead fish driven by the current, and being distressed by the heat and foul smell, were compelled to turn back. One of the boats which approached the nearest lost some of her crew,

and was scarcely able to reach Lipari with the rest, and they had fits like an epileptic person, at one time fainting and giddy, and at another returning to their senses; and many days afterwards a mud or clay was observed rising in the sea, and in many parts the flames issued, and smoke and smoky blazes; afterwards it congealed and became a rock like mill-stones. Titus Flaminus, who then commanded in Sicily, despatched to the senate (of Rome) a full account of the phenomenon; the senate sent and offered sacrifieces to the infernal and marine divinities both in the little island (which had thus been formed) and the Lipari Islands."

Strabo mentions (Book viii., Chap. vi., § 19, Vol. II., p. 59) the cities enumerated in Homer's Catalogue of Ships (Illiad, ii., 569) including "spacious Helike" (Ἑλίκην εὐρεῖαν). In Book viii., Chap. vii., § 2; pp. 69–70, he recounts the development of Achaian power, and say they began in the time of Pyrrhus with four cities:

"They then had an accession of the twelve cities, with the exception of Olenus and Helice; the former refused to join the league; the other was swallowed up by the waves.

"For the sea was raised to a great height by an earthquake, and overwhelmed both Helice and the temple of the Heliconian Neptune, whom the Ionians still hold in great veneration, and offer sacrifices to his honour. They celebrate at that spot the Panionian festival. According to the conjecture of some persons, Homer refers to these sacrifices in these lines,

"'But he breathed out his soul, and bellowed, as a bull
Bellows when he is dragged round the altar of the Heliconian king.'

"It is conjectured that the age of the poet is later than the migration of the Ionian colony, because he mentions the Panionian sacrifices, which the Ionians perform in honour of the Heliconian Neptune in the territory of Priene; for the Prienians themselves are said to have come from Helice; a young man also of Priene is appointed to preside as king at these sacrifices, and to superintend the celebration of the sacred rites. A still stronger proof is adduced from what is said by the poet respecting the bull, for the Ionians suppose, that sacrifice is performed with favorable omen, when the bull bellows at the instant that he is wounded at the altar.

"Others deny this, and transfer to Helice the proofs alleged of the bull and the sacrifice, asserting that these things were done there by established custom, and that the poet drew his comparison from the festival celebrated there. Helice was overwhelmed by the waves two years before the battle of Leuctra. Eratosthenes says, that he himself saw the place, and the ferrymen told him that there formerly stood in the strait a brazen statue of Neptune, holding in his hand a hippocampus, an animal which is dangerous to fishermen.

"According to Heracleides, the inundation took place in his time, and during the night. The city was at the distance of twelve stadia from the sea, which overwhelmed the whole intermediate country as well as the city. Two thousand men were sent by the Achæans to collect the dead bodies, but in vain. The territory was divided among the bordering people. This

calamity happened in consequence of the anger of Neptune, for the Ionians, who were driven from Helice, sent particularly to request the people of Helice to give them the image of Neptune, or if they were unwilling to give that, to furnish them with the model of the temple. On their refusal, the Ionians sent to the Achæan body, who decreed, that they should comply with the request, but they would not obey even this injunction. The disaster occurred in the following winter, and after this the Achæans gave the Ionians the model of the temple."

§ 21. *The Theory of Pliny (23–79 A.D.).*

The following extracts are taken from Bohn's excellent translation of the "Natural History." They exhibit the views of Pliny, who follows closely the theory of Aristotle.

In Book II., of the Natural History, will be found Pliny's account of earthquakes, which runs thus:

"CHAP. 81 (79)—OF EARTHQUAKES.

"According to the doctrine of the Babylonians,[1] earthquakes and clefts of the earth, and occurrences of this kind, are supposed to be produced by the influence of the stars, especially of the three to which they ascribe thunder (Saturn, Jupiter and Mars); and to be caused by the stars moving with the sun, or being in conjunction with it, and, more particularly, when they are in the quartile aspect. If we are to credit the report, a most admirable and immortal spirit, as it were of a divine nature, should be ascribed to Anaximander the Milesian, who, they say, warned the Lacedæmonians to beware of their city and their houses. For he predicted that an earthquake was at hand, when both the whole of their city was destroyed and a large portion of Mount Taygetus, which projected in the form of a ship, was broken off, and added farther ruin to the previous destruction. Another prediction is ascribed to Pherecydes, the master of Pythagoras, and this was divine; by a draught of water from a well, he foresaw and predicted that there would be an earthquake in that place. And if these things be true, how nearly do these individuals approach to the Diety, even during their lifetime! But I leave every one to judge of these matters as he pleases. I certainly conceive the winds to be the cause of earthquakes; for the earth never trembles except when the sea is quite calm, and when the heavens are so tranquil that the birds cannot maintain their flight, all the air which should support them being withdrawn; nor does it ever happen until after great winds, the gust being pent up, as it were, in the fissures and concealed hollows. For the trembling of the earth resembles thunder in the clouds; nor does the yawning of the earth differ from the bursting of the lightning; the enclosed air struggling and striving to escape.

"CHAP. 82 (80)—OF CLEFTS OF THE EARTH.

"The earth is shaken in various ways, and wonderful effects are produced; in one place the walls of cities being thrown down, and in others swallowed up by a deep cleft; sometimes great masses of earth are heaped

[1] Pliny here refers to the Astrologers, who were said to have come originally from Babylon.

up, and rivers forced out, sometimes even flame and hot springs, and at others the course of rivers is turned. A terrible noise precedes and accompanies the shock; sometimes a murmuring, like the lowing of cattle, or like human voices, or the clashing of arms. This depends on the substance which receives the sound, and the shape of the caverns or crevices through which it issues; it being more shrill from a narrow opening, more hoarse from one that is curved, producing a loud reverberation from hard bodies, a sound like a boiling fluid from moist substances, fluctuating in stagnant water, and roaring when forced against solid bodies. There is, therefore, often the sound without any motion. Nor is it a simple motion, but one that is tremulous and vibratory. The cleft sometimes remains, displaying what it has swallowed up; sometimes concealing it, the mouth being closed and the soil being brought over it, so that no vestige is left; the city being, as it were, devoured, and the tract of country engulfed. Maritime districts are more especially subject to shocks. Nor are mountainous tracts exempt from them; I have found, by my inquiries, that the Alps and the Apennines are frequently shaken. The shocks happen more frequently in the autumn and in the spring, as is the case also with thunder. There are seldom shocks in Gaul and in Egypt; in the latter it depends on the prevalence of summer, in the former of winter. They also happen more frequently in the night than in the day. The greatest shocks are in the morning and the evening; but they often take place at daybreak, and sometimes at noon. They also take place during the eclipses of the sun and of the moon, because at that time storms are lulled. They are most frequent when great heat succeeds to showers, or showers succeed to great heat.

"CHAP. 83 (81)—SIGNS OF AN APPROACHING EARTHQUAKE.

"There is no doubt that earthquakes are felt by persons on shipboard, as they are struck by a sudden motion of the waves, without these being raised by any gust of wind. And things that are in the vessels shake as they do in houses, and give notice by their creaking; also the birds, when they settle upon the vessels, are not without their alarms. There is also a sign in the heavens; for, when a shock is near at hand, either in the daytime or a little after sunset, a cloud is stretched out in the clear sky, like a long thin line. The water in wells is also more turbid than usual, and it emits a disagreeable odour.

"CHAP. 84 (82)—PRESERVATIVES AGAINST FUTURE EARTHQUAKES.

"These same places, however, afford protection, and this is also the case where there is a number of caverns, for they give vent to the confined vapour, a circumstance which has been remarked in certain towns, which have been less shaken where they have been excavated by many sewers. And, in the same town, those parts that are excavated are safer than the other parts, as is understood to be the case at Naples in Italy, the part of which is solid being more liable to injury. Arched buildings are also the most safe, also the angles of walls, the shocks counteracting each other; walls made of brick also suffer less from the shocks. There is also a great difference in the nature of the motions, where various motions are experienced.

It is safest when it vibrates and causes a creaking in the building, and where it swells and rises upwards, and settles with an alternate motion. It is also harmless when the buildings coming together butt against each other in opposite directions, for the motions counteract each other. A movement like the rolling of waves is dangerous, or when the motion is impelled in one direction. The tremors cease when the vapour bursts out; but if they do not soon cease, they continue for forty days; generally, indeed, for a longer time: some have lasted even for one or two years.

"CHAP. 85 (83)—PRODIGIES OF THE EARTH WHICH HAVE OCCURRED ONCE ONLY.

"A great prodigy of the earth, which never happened more than once, I have mentioned in the books of the Etruscan ceremonies, as having taken place in the district of Mutina, during the consulship of Lucius Martius and Sextus Julius. Two mountains rushed together, falling upon each other with a very loud crash, and then receding; while in the daytime flame and smoke issued from them; a great crowd of Roman knights, and families of people, and travellers on the Æmilian way, being spectators of it. All the farm-houses were thrown down by the shock, and a great number of animals that were in them were killed; it was in the year before the Social war; and I am in doubt whether this event or the civil commotions were more fatal to the territory of Italy. The prodigy which happened in our own age was no less wonderful; in the last year of the emperor Nero, as I have related in my history of his times, when certain fields and olive grounds in the district of Marrucinum, belonging to Vectius Marcellus, a Roman knight, the steward of Nero, changed places with each other, although the public highway was interposed.

"CHAP. 86 (84)—WONDERFUL CIRCUMSTANCES ATTENDING EARTHQUAKES.

"Inundations of the sea take place at the same time with earthquakes; the water being impregnated with the same spirit, and received into the bosom of the earth which subsides. The greatest earthquake which has occurred in our memory was in the reign of Tiberius, by which twelve cities of Asia were laid prostrate in one night. They occurred the most frequently during the Punic war, when we had accounts brought to Rome of fifty-seven earthquakes in the space of a single year. It was during this year that the Carthagenians and the Romans, who were fighting at the lake Thrasimenus, were neither of them sensible of a very great shock during the battle. Nor is it an evil merely consisting in the danger which is produced by the motion; it is an equal or a greater evil when it is considered as a prodigy. The city of Rome never experienced a shock, which was not the forerunner of some great calamity.

"CHAP. 87 (85)—IN WHAT PLACE THE SEA HAS RECEDED.

"The same cause produces an increase of the land; the vapour, when it cannot burst out forcibly lifting up the surface. For the land is not merely produced by what is brought down the rivers, as the islands called Echinades are formed by the river Achelous, and the greater part of Egypt by the Nile, where, according to Homer, it was a day and a night's journey from

the mainland to the island of Pharos; but in some cases, by the receding of the sea, as, according to the same author, was the case with the Circæan isles. The same thing also happened in the harbour of Ambracia, for a space of 10,000 paces, and was also said to have taken place for 5000 at the Piræus of Athens, and likewise at Ephesus, where formerly the sea washed the walls of the temple of Diana. Indeed, if we may believe Herodotus, the sea came beyond Memphis, as far as the mountains of Æthiopia, and also from the plains of Arabia. The sea also surrounded Ilium and the whole of Teuthrania, and covered the plain through which the Mæander flows.

CHAP. 88 (86)—THE MODE IN WHICH ISLANDS RISE UP.

"Land is sometimes formed in a different manner, rising suddenly out of the sea, as if nature was compensating the earth for its losses, restoring in one place what she had swallowed up in another.

"CHAP. 89 (87)—WHAT ISLANDS HAVE BEEN FORMED, AND AT WHAT PERIODS.

"Delos and Rhodes, islands which have now been long famous, are recorded to have risen up in this way. More lately there have been some smaller islands formed; Anapha, which is beyond Melos; Nea, between Lemnos and the Hellespont; Halone, between Lebedos and Teos; Thera and Therasia, among the Cyclades, in the fourth year of the 135th Olympiad. And among the same islands, 130 years afterwards, Hiera, also called Automate, made its appearance; also Thia, at the distance of two stadia from the former, 110 years afterwards, in our own times, when M. Junius Silanus and L. Balbus were consuls, on the 8th of the ides of July.

"88. Opposite to us, and near to Italy, among the Æolian isles, an island emerged from the sea; and likewise one near Crete, 2,500 paces in extent, and with warm springs in it; another made its appearance in the third year of the 163rd Olympiad, in the Tuscan gulf, burning with a violent explosion. There is a tradition too that a great number of fishes were floating about the spot, and that those who employed them for food immediately expired. It is said that the Pithecusan isles rose up, in the same way, in the bay of Campania, and that shortly afterwards, the mountain Epopos, from which flame had suddenly burst forth, was reduced to the level of the neighbouring plain. In the same island, it is said, that a town was sunk in the sea; that in consequence of another shock, a lake burst out, and that, by a third, Prochytas was formed into an island, the neighbouring mountains being rolled away from it.

"CHAP. 90—LANDS WHICH HAVE BEEN SEPARATED BY THE SEA.

"In the ordinary course of things islands are also formed by this means. The sea has torn Sicily from Italy, Cyprus from Syria, Eubœa from Bœotia. Atalante and Macris from Eubœa, Besbycus from Bithynia, and Leucosia from the promontory of the Sirens.

"CHAP. 91 (89)—ISLANDS WHICH HAVE BEEN UNITED TO THE MAINLAND.

"Again, islands are taken from the sea and added to the mainland; Antissa to Lesbos, Zephyrium to Halicarnassus, Æthusa to Myndus, Dro-

miscus and Perne to Miletus, Narthecusa to the promontory of Parthenium. Hybanda, which was formerly an island of Ionia, is now 200 stadia distant from the sea. Syries is now become a part of Ephesus, and, in the same neighborhood, Derasidas and Sophonia form part of Magnesia; while Epidaurus and Oricum are no longer islands.

"CHAP. 92 (90)—LANDS WHICH HAVE BEEN TOTALLY CHANGED INTO SEAS.

"The sea has totally carried off certain lands, and first of all, if we are to believe Plato, for an immense space where the Atlantic ocean is now extended. More lately we see what has been produced by our inland sea; Acarnania has been overwhelmed by the Ambracian gulf, Achaia by the Corinthian, Europe and Asia by the Propontis and Pontus. And besides these, the sea has rent asunder Leucas, Antirrhium, the Hellespont, and the two Bosphori.

"CHAP. 93 (91)—LANDS WHICH HAVE BEEN SWALLOWED UP.

"And not to speak of bays and gulfs, the earth feeds on itself; it has devoured the very high mountain of Cybotus, with the town of Curites; also Sipylus in Magnesia, and formerly, in the same place, a very celebrated city, which was called Tantalis; also the land belonging to the cities Galanis and Gamales in Phœnicia, together with the cities themselves; also Phegium, the most lofty ridge in Æthiopia. Nor are the shores of the sea more to be depended upon.

"CHAP. 94 (92)—CITIES WHICH HAVE BEEN ABSORBED BY THE SEA.

"The sea near the Palus Mæotis has carried away Pyrrha and Antissa, also Elice and Bura in the gulf of Corinth, traces of which places are visible in the ocean. From the island Cea it has seized on 30,000 paces, which were suddenly torn off, with many persons on them. In Sicily also the half of the city of Tyndaris, and all the part of Italy which is wanting; in like manner it carried off Eleusina in Bœotia.

Again:

"CHAP. 110 (106)—PLACES WHICH ARE ALWAYS BURNING.

"Among the wonders of mountains there is Ætna, which always burns in the night, and for so long a period has always had materials for combustion, being in the winter buried in snow, and having the ashes which it has ejected covered with frost. Nor is it in this mountain alone that nature rages, threatening to consume the earth; in Phaselis, the mountain Chimæra burns, and indeed with a continual flame, day and night. Ctesias of Cnidos informs us, that this fire is kindled by water, while it is extinguished by earth and by hay. In the same country of Lycia, the mountains of Hephæstius, when touched with a flaming torch, burn so violently, that even the stones in the river and the sand burn, while actually in the water; this fire is also increased by rain. If a person makes furrows in the ground with a stick which has been kindled at this fire, it is said that a stream of flame will follow it. The summit of Cophantus, in Bactria, burns during the night and this is the case in Media and at Sittacene, on the borders of Persia;

likewise in Susa, at the White Tower, from fifteen apertures, the greatest of which also burns in the daytime. The plain of Babylon throws up flame from a place like a fish-pond, an acre in extent. Near Hesperium, a mountain of the Æthiopians, the fields shine in the night-time like stars; the same thing takes place in the territory of the Megalopolitani. This fire, however, is internal, mild, and not burning the foliage of a dense wood which is over it. There is also the crater of Nymphæum, which is always burning, in the neighbourhood of a cold fountain, and which, according to Theopompus, presages direful calamities to the inhabitants of Apollonia. It is increased by rain, and it throws out bitumen, which, becoming mixed with the fountain, renders it unfit to be tasted; it is, at other times, the weakest of all the bitumens. But what are these compared to other wonders? Hiera, one of the Æolian isles, in the middle of the sea, near Italy, together with the sea itself, during the Social war, burned for several days, until expiation was made, by a deputation from the senate. There is a hill in Æthiopia called Θεῶν ὄχημα, which burns with the greatest violence, throwing out flame that consumes everything, like the sun. In so many places, and with so many fires, does nature burn the earth!"

"CHAP. III (107)—WONDERS OF FIRE ALONE.

"But since this one element is of so prolific a nature as to produce itself, and to increase from the smallest spark, what must we suppose will be the effect of all those funeral piles of the earth? What must be the nature of that thing, which, in all parts of the world, supplies this most greedy voracity without destroying itself? To these fires must be added those innumerable stars and the great sun itself. There are also the fires made by men, those which are innate in certain kinds of stone, those produced by the friction of wood, and those in the clouds, which give rise to lightning. It really exceeds all other wonders, that one single day should pass in which everything is not consumed, especially when we reflect that concave mirrors placed opposite to the sun's rays produce a flame more readily than any other kind of fire; and that numerous small but natural fires abound everywhere. In Nymphæum there issues from a rock a fire which is kindled by rain; it also issues from the waters of the Scantia. This indeed is a feeble flame, since it passes off, remaining only a short time on any body to which it is applied: an ash tree, which overshadows this fiery spring, remains always green. In the territory of Mutina fire issues from the ground on the days that are consecrated to Vulcan. It is stated by some authors, that if a burning body falls on the fields below Aricia, the ground is set on fire; and that the stones in the territory of the Sabines and of the Sidicini, if they be oiled, burn with flame. In Egnatia, a town of Salentinum, there is a sacred stone upon which, when wood is placed, flame immediately bursts forth. In the altar of Juno Lacinia, which is in the open air, the ashes remain unmoved, although the winds may be blowing from all quarters.

"It appears also that there are sudden fires both in waters and even in the human body; that the whole Lake Thrasymenus was on fire; that when Servius Tullius, while a child, was sleeping flame darted out from his head; and Valerius Antias informs us, that the same flame appeared about L.

Marcius, when he was pronouncing the funeral oration over the Scipios, who were killed in Spain; and exhorting the soldiers to avenge their death. I shall presently mention more facts of this nature, and in a more distinct manner; in this place these wonders are mixed up with other subjects. But my mind, having carried me beyond the mere interpretation of nature, is anxious to lead, as it were by the hand, the thoughts of my readers over the whole globe."

In Book III., Chapter 14, Pliny discusses the volcanoes in the Æolian Islands. Book iv., Chapter 6, contains an account of Achaia, in which Pliny mentions the destruction of Helike and Bura, and the towns in which the people who escaped the inundation of the sea afterwards took refuge. After enumerating the cities of Achaia he adds:

"Throughout the whole of this region, as though nature had been desirous to compensate for the inroads of the sea, seventy-six mountains raise their lofty heads." (Book iv., Chap. 10.)

Pliny has the following remarks on the island of Delos (Lib. IV., Chap. 22, pp. 318–319):

"This island long floated on the waves, and, as tradition says, was the only one that had never experienced an earthquake, down to the time of M. Varro; Mucianus however has informed us, that it has been twice so visited. Aristotle states that this island received its name from the fact of its having so suddenly made its appearance on emerging from the sea; Aglaosthenes, however, gives it the name of Cynthia, and others of Ortygia, Asteria, Lagia, Chlamydia, Cynthus, and from the circumstance of fire having been first discovered here, Pyrpile. Its circumference is five miles only; Mount Cynthus here raises his head."

The reader will see from these accounts that Pliny follows Aristotle and Strabo. They all hold that earthquakes are due to the efforts of elastic vapors to escape through the ground and diffuse themselves in the atmosphere. In Chapter 82 (80), Book II., Pliny remarks: "Maritime districts are more especially subject to shocks." Whether this is an independent observation, or he merely followed the sagacious remarks of Aristotle, whose remarkable theory we have translated in section 19, the statement is equally interesting and true.

If then earthquakes are especially frequent in maritine districts, and are due to efforts of elastic vapors seeking to diffuse themselves in the atmosphere, may it not be justly said that although they did not have a satisfactory explanation of the penetration of the vapors into the earth, the leading philosophers of Greece and

Rome came very near the true theory of earthquakes as we conceive it to-day?

V. On the Ancient and Modern Theory of Earthquakes, on the Sinking of Helike, and on the Movements Taking Place in the Ægean and Asia Minor.

§ 22. *Common Views of Plato, Aristotle, Strabo and Pliny.*

From the accounts quoted in the foregoing extracts, we have seen that Plato held that air and water, entering through hollows and crevices, obtained access to the bowels of the earth, and that there are everywhere beneath the earth rivers and lakes of fire (Pyriphlegethon), some of which he had seen emitted from Mt. Ætna. Owing to his pictorial style of exposition Plato's accounts are more or less allegorical, but these general results seem sufficiently clear to be beyond doubt. Aristotle was trained under Plato, but he afterwards departed from the style of composition employed in the Academy, and adopted in all his mature writings the modern scientific method of simple direct statement of facts.

Accordingly in the writings of Aristotle we see the theory of earthquakes as taught by the master mind during the culmination of the physical philosophy of the Greeks. Aristotle was not only the greatest natural philosopher of Greece, but of antiquity, and one of the most luminous intellects of all time. No other mind of any age or country has exerted so great an influence on scientific thought or on its terminology. Thus Eusebius designates him as "Nature's private Secretary," while Dante calls him the "master of those who know," in reference no doubt especially to his development of the methods of logic. But Aristotle's genius extended to every branch of human knowledge, and ornamented everything it touched.

In spite of some errors, incident to the early age in which he lived, his observations of nature show the highest order of sagacity and mental penetration, and will always give him the foremost place among the philosophers of antiquity. In his mental activity he felt the necessity for physical laws, and thus became accustomed to seek the *causes* of things; so that in Strabo we find complaint of his depth of thought. His mind was therefore preëminently scientific in the highest sense of the word, and no modern thinker has surpassed him in subtileness and power of intuition.

Like Plato he recognized water and air as entering into the bowels of the globe, through hollows, caverns and fissures; and there, in contact with the internal heat, giving rise to imprisoned vapor, which develops such force that it brings on an earthquake. He fully recognized the prevalence of earthquakes in maritime regions, and on this point his views have been adopted by Strabo and Pliny.

In the time of Aristotle the universe was conceived as made up of four elements, fire, air, water, and earth. But the Greeks noticed the evaporation of water, and its precipitation from the clouds in the form of rain, hail and snow; and they recognized that there was some process by which it became invisible, and was afterwards condensed into clouds and precipitated by atmospheric agencies. Aristotle does not usually distinguish vapor of steam from air, though occasionally he calls steam ἀτμίς, while ordinary wind is called ἄνεμος. He must have conceived the two vapors as passing by some unknown process one into the other.

Accordingly when he says vapor, air, or wind, we are often to understand not only atmospheric air, but also a mixture of vapor of steam. Since such vapor is seen to be emitted by volcanoes, as in the case he mentions of the Æolian Island Hiera, now called Vulcano, he naturally and correctly reasons that it was the cause of that violent outbreak.[1] In like manner Aristotle holds that vapor is the cause of the agitation of the earth even when no surface eruption occurs. He recognized therefore that the tension of elastic vapor seeking to diffuse itself in the atmosphere may become so powerful as to overcome the confining rocks of the earth's crust, and bring on an earthquake, even though none escapes to the surface, but the whole of it remains hidden in the earth. In this view he is followed by Lucretius, Strabo, and Pliny. How much more

[1] Paulus Orosius (Lib. LV., Cap. 20) says that this island, which was often called Thermessa by the ancients, arose from the sea in the year 571 B.C. A passage in Thucydides (Lib. III., § 88) shows that it was in existence in 427 B.C. (cf. Strabo's Geography, Bohn's Transl., vol. 1, p. 417, footnote). This date of 571 B.C. is consistent with the date given by Aristotle. Pliny's statement (Lib. II., Cap. 89; Vol. 1, p. 118) is incorrect, and may perhaps be explained by a transcriber's error, or by some confusion of Pliny himself. Perhaps Thermessa was confounded with Therasia near Thera.

philosophical and accordant with Newton's rule this is than the singular modern method of dividing earthquakes into two separate classes, volcanic and tectonic!

Aristotle holds not only that earthquakes are due to vapor in the earth, but also that they are most prevalent near the sea. In other parts of the "Meteorology" (Lib. 1, Cap. iv.), he says that the "distribution of land and sea in particular regions does not endure throughout all time, but it becomes sea in those parts where it was land, and again it becomes land where it was sea"; and finally adds "everything changes in the course of time." Aristotle also correctly associated seismic sea waves with earthquakes, and points out cases of islands and volcanoes upheaved in the sea. The philosophical position which he occupied was thus extraordinarily advanced, and there is little wonder that his views were adopted and elaborated by Strabo and Pliny. This simple and orderly development of thought among the ancients is in melancholy contrast to the disconnected and anachronous views still prevalent on these subjects in our own time.

§ 23. *Explanation of the Sinking of Helike and destruction of Bura, 373 B.C.*

We have seen that Strabo says that Helike sank in the night,[1] after the region had been shaken by a great earthquake. He says Helike was 12 stadia from the sea, and Bura 40 stadia, about 1.5 and 5 miles respectively. In his large work on the "Face of the Earth" (Vol. II., pp. 448, 464) Professor Suess explains this sinking by the shaking down of an alluvial deposit, which broke loose from the older formation, thus causing it to slip into the sea. The process described by Suess is a familiar one where a narrow band of soil is formed near steep cliffs; but this shaking lose obviously could not occur where the extent of the deposit is from 1.5 to 5 miles in width. No alluvial deposit of this width would slide during an earthquake, unless it was on the slope of a comparatively steep mountain, and the strata under it were inclined at a steep angle, of say 30°, which was not the case in the region of Helike and Bura. These cities were both built on decidedly solid lowlands along the seashore, and with such a broad base the alluvial deposits could not slide into the sea. What J. Schmidt ob-

[1] According to Heracleides.

served in the same region after the earthquake which shook Ægion, December 26, 1861, may possibly have been due to the settlement of the alluvium, but it is much more probable that it arose from a sinking of the crust along the line of a hidden fault, similar to that which so severely rent the ground under Bura in 373 B.C.

It is usually stated that Bura was covered by the sea like Helike, but some of the ancient authors correctly imply that the ruin was mainly due to the opening of fissures of the earth, which caused the houses to be engulfed. Others say that it was also covered by the sea, but both here and at Helike some objects remained above the water. Bura, however, was built on a hill and ruins of it are still extant at considerable elevation above the sea level.

The land which sank when Helike was submerged beneath the waves was evidently similar to that now seen along the southern shore of the gulf of Corinth. A railroad now traverses this shore almost the entire length of the gulf. While on a visit to Dèlphi early in April, 1891, the writer crossed the gulf in a sail boat, and took the train for Olympia near this ancient site of Helike and Bura. The lay of the land is gentle and nowhere is the ascent other than very gradual. The mountains of Arcadia are quite a distance away, but usually visible to the traveler. From my own observations of the southern shore of the gulf, along the region where Helike now lies beneath the waves, I feel sure that the land of this entire region is too solid to experience appreciable settling under the shaking of an earthquake. What then was the cause of the disaster of 373 B.C.?

In the paper on the cause of earthquakes, we have seen that in world-shaking seismic disturbances lava moves beneath the crust, and usually is expelled from under the bed of the sea. After the crust is thus undermined, the sea bottom frequently subsides, and the sinking of the bed of the sea draws the water away from the shore and causes the seismic sea waves. The gulf of Corinth is a sea trough, with high mountains on both sides; and in 373 B.C. lava was expelled from under it and pushed under the mountains to the north or south—most likely under the Arcadian mountains to the south; and after the lava was expelled the bed of the trough sank down, carrying with it the shores on which Helike stood.

The mountains north of Delphi, including Parnassus and Helicon, as well as those further west in Ætolia, like those to the south in Arcadia, have all been pushed up by the expulsion of lava from beneath the gulf of Corinth. Now the accounts of the destruction of Helike show that the region was first terribly shaken by an earthquake, obviously by the movement of lava streams beneath the crust, what Plato would perhaps call Pyriphlegethon, and then inundated by the sea, the town afterwards remaining largely or wholly under water. This can only mean that the bottom of the gulf gave down, and carried the southern shore down with it; perhaps the fault which moved is beneath the deep soil and did not show at the surface, except in the chasms which appeared at Bura, as mentioned by Aristotle. If alluvium of such great age could settle at all under the shaking of an earthquake, the amount of the subsidence could not exceed a very few feet. This was found to be true of the soft land at San Francisco which had been made within a quarter of a century before the great earthquake of April 18, 1906, and the same conclusion is drawn from observations of many other great earthquakes of recent years. Such shaking down would not be adequate to account for the submergence of Helike beneath the waves.

This town could hardly have been less than 50 feet above the sea level of the gulf, and a height of 80 feet is much more probable, owing to the universal custom of the Greeks of building a town always on the highest available point and crowning it with an Acropolis, containing the temples of the gods. The houses would be at least 20 feet high, so that the subsidence must have been at least 70 feet, and it was more probably from 80 to 100 feet. The amount of the subsidence, even if we take the lowest figure, 70 feet, is altogether too great to be accounted for by mere shaking down of alluvium deposited hundreds of thousands of years ago. And the distance from the sea mentioned by Strabo, who could not well be mistaken, shows that a sliding of the whole broad alluvial deposit could not have taken place.

Moreover, the account given by Aristotle, within whose lifetime the event had occurred, implies that the seismic sea wave was of that class in which the water first retires from the shore (πρόωσις)

and then returns after the currents have met and raised a ridge in the centre of the depression. By no possibility can we interpret Aristotle's account to indicate an elevation of the sea bottom, as when a volcano is upheaved, which would cause the waters to rise suddenly without previous recession from the shore. The only other class of sea waves is that in which the water retires after the earthquake, and Aristotle's language distinctly implies that this recession took place. Moreover, Strabo says that the disaster was attributed to the anger of Poseidon, "the earth-shaker," to whom were ascribed the sea waves accompanying great earthquakes.

If this view be admissible, it will follow that the sinking of Helike was by the usual process of subsidence in seismic sea waves of the first class, except that the subsidence of the bottom of the gulf carried down also part of the shore. As the gulf is quite narrow such a result is probable in the highest degree.

This sinking of the shore along the bed of the sea is not unusual even where the sea is wide; but for the sake of convenience of diction we have ordinarily spoken only of the sinking of the sea bottom rather than of the land along the shore. Unless there is movement of a fault with vertical walls, the change of level is naturally gradual, depending on the yielding and flexure of the earth's crust when lava is injected or expelled from beneath it.

§ 24. *Further Considerations on the Elevation of the Himalayas, Based on the Relief of the Indian Ocean at its Margins.*

In the paper on the cause of earthquakes we have explained the Himalayas by the expulsion of lava from beneath the Indian Ocean, and have attributed the continuance of earthquakes in that region to the activity of the ancient sea trough where the Ganges and Bramaputra now flow. The process there is similar to that found in the Andes, but the mountains are now somewhat further from the sea. In calling attention to the surface leakage in the region south of the Himalayas, there was no thought of implying that the effect of the ocean has ceased; on the contrary there can be no doubt that strain beneath the Indian Ocean's crust is still relieved by the same movements which originally formed and are still raising the Himalaya mountains. The surface waters augment the effects of the relief of strain from beneath the sea, and these two

causes together produce the observed earthquakes. This explains the occurrence of a large earthquake belt south of the Himalayas, the existence of which heretofore has been so perplexing. Where the crust is badly broken and fissured, the surface water more readily aids the original tendency to relief, depending on the secular leakage of the adjacent ocean. We have treated this question in section 20 of the paper on the cause of earthquakes, but the Himalayas were not treated in great detail, and it seemed well to point out specifically that the same tendency to relief, which we find around the margins of the Pacific, holds equally true in the great western extension known as the Indian Ocean. Here at present relief is obtained chiefly along the northern and northeastern borders, though some is afforded in islands and various other places. The Indian Ocean not only has high mountains on its margins, but also a considerable number of islands and volcanoes. In this respect it resembles the Pacific.

A study of the principal mountain chains suggests that whenever a serious break has once occurred in the crust of the earth, the strain arising in the underlying layer continues to find relief by the escape of steam-saturated lava into the avenue thus opened, which is the path of least resistance. The formation of the Alps, Andes and other mountains, as well as the Himalayas, illustrate this principle.

Whether the motion of lava towards the avenue of escape is by creeping flow, or by small earthquakes, we do not know; possibly it may be by both methods. It is only in violent world-shaking earthquakes that we can be sure that lava is moved beneath the crust *en mass* over considerable distances. These streams of lava are proved to exist by the uplift of coasts and by the sinking of the sea bottom implied in seismic sea waves.

Such subterranean movements correspond closely to Plato's Pyriphlegethon, but when once a fault has moved for a long time upward, the strain may become so great from the way in which the blocks of the earth's crust are wedged together, that the upward movement there becomes more difficult, and a neighboring region affords easier relief. And in pushing up the neighboring area, the previously elevated block may be let down again, by the relief

thereby afforded beneath. Thus a mountain system such as the Himalayas, Alps or Andes represents a vast number of such elevations and depressions, and this is the way in which such movements are to be explained. A theory which is capable of furnishing such a simple explanation of such complex phenomena should have a strong claim to acceptance.

The principal escapes from the Indian Ocean seem to be chiefly under the mouths of the Ganges and Indus, and hence we see why these regions are so often disturbed by violent earthquakes. It is noticeable that few important changes of level have been produced there, except subsidence, because these troughs were arched downward, and the surface movement therefore usually has been small.

Some geologists have inferred that earthquakes are common in the deltas of all great rivers. But observation shows that this is not universally, nor even commonly, true. The deltas of the Mississippi and Amazon, so far as known, have never experienced severe earthquakes, and if deposits of sediment were the cause they ought to have felt disturbances like those which have been frequent in the deltas of the Ganges and Indus. But there is an important difference between the Ganges and the Indus, on the one hand, and the Mississippi and Amazon on the other. Under the former are avenues of escape for the steam-saturated lava forming under the Indian Ocean, while little if any escape takes place at the mouth of the Mississippi and Amazon. The Gulf of Mexico is only moderately deep and the crust broken and faulted chiefly on the side towards Mexico, hence the earthquakes occur there; the Atlantic in the region of the Amazon is shallow, and the crust along the coast but little broken.

It appears therefore that the claim that earthquakes occur in the deltas of great rivers must be given up. Thus we get also a clearer view of the relief of the Indian Ocean, by which the Himalayas were formed; and the earthquakes occuring there now become more intelligible.

§ 24. *On Professor Suess' Theory that the Ægean Sea has Collapsed within Recent Geological Time, and on the Origin and Secular Movements of Asia Minor and Syria.*

Professor Suess holds that the basin of the Ægean Sea has sunk

down in recent geological time; and on the assumption that the globe is shrinking, he thinks the whole of Asia Minor may some day collapse, and thus connect the Pontus and the Caspian directly with the Mediterranean. According to the view here adopted nothing could be further from the truth than such an hypothesis. For, in the first place, we have shown that as the effect of cooling is insensible, the earth is not contracting; and, in the second place, that the movements of the crust are due to the action of a substratum just beneath, which in earthquakes behaves as fluid.

Moreover, the relative situation of the rocks about the Ægean Sea will be the same whether that sea has recently sunk down, or the whole of Asia Minor has been raised up. There is no historical evidence of the sinking of the Ægean Sea, except that furnished by the disturbances due to earthquakes, and the geological evidence is capable of a double interpretation. The prevalence of earthquakes in Asia Minor is a proof that subterranean movement is now going on there; otherwise such places as Apamea in Phrygia, Smyrna, Mitilene, Antioch and numerous other cities would not have suffered so much from earthquakes within historical times. The whole coast of Asia Minor and of Syria has been subject to severe earthquakes since the earliest ages; and the ruins of temples at such places as Palmyra and Balbec are to be explained partly by the effects of political revolutions and partly by the ravages of time, but more especially by the leveling influence of earthquakes.

In his work on "Earthquakes in the Light of the new Seismology," Major Dutton gives an account of the different kinds of seismic sea waves, and remarks that those in the eastern Mediterranean have usually been characterized by a preliminary withdrawal of the water before the wave returns to inundate the shore. Such waves are the only kind mentioned by Aristotle, which shows that they were familiar to the Greeks at an early age.

Now if the waves are predominantly of this class, just as along the west coast of South America, it follows that the sea bottom sinks, and has therefore been undermined in the process of elevating the mountains and the coasts. Asia Minor and Syria are covered with mountains of a complex character, and many movements of these mountains have been observed within the period

covered by history. No doubt the general movement is one of elevation, which corresponds to the sinking of the sea bottom implied in the seismic sea waves observed to come ashore after the terrible earthquakes by which the region is afflicted.

As the mountains are of recent formation, and extend entirely across Asia Minor, we may not hesitate in the belief that the whole of that region has been elevated within recent geological time. The sinking of the sea bottom prevailing in that part of the Mediterranean has often carried down the shores with it; but in a number of cases elevation has also taken place. Strabo, among the ancients, gives evidence bearing on this question; and Professor Suess, among the moderns, cites important changes which have taken place since the age of the Greeks. In "The Face of the Earth" (Vol. II., pp. 448–453), Suess mentions the subsidence of Smyrna and of the famous mausoleum in the Bay of Makri, as well as changes of level at Mitylene, Mermiridje and other places. It would be moderate to say that his explanations seem highly improbable, and it is really impossible that all of them can be correct. They rest on no general principle, but rather on improvised hypotheses.

The mausoleum at Makri can hardly have slid with the alluvial soil into the bay, as he maintains; for, judging by the photograph of the mauseleum which he gives, the alluvial base is not less than a mile wide, and thus would not slip, unless the substratum of rock were greatly inclined, which does not seem to be the case. The adjacent sea appears to be shallow, and all these circumstances are against the theory. Finally it is unlikely that the alluvium could be sufficiently settled by an earthquake to bring the mausoleum down to the level of the water, so that the tides would cover the lower part of it. It must have stood originally not less than 20 feet above the sea level, and 60 feet is a much more probable elevation. It is thus practically certain that the shore was carried down in the subsidence of the sea bottom, as happened when Helike sank beneath the waves in B. C. 373. In the case of the mausoleum the submergence may have been either sudden, or gradual. Darwin and Fitzroy observed the Chilean coast to subside slowly after it had been pushed up by the earthquake of 1835, and these slow move-

ments frequently occur, but are seldom recorded, because so much less obvious than sudden changes of level. In this way we may explain the changes of level at the Troad, Ephesus, the Peireus and other places mentioned by Strabo.

In the "Face of the Earth" (Vol. II., pp. 450–451), Professor Suess discusses the supposed changes in the level of the coast road on the Climax mountains in Pamphylia; and quotes Luschan, who says that "the sandy ground at the foot of these steep cliffs, which formerly offered a practicable road, is now (January, 1885) covered by the sea to a depth of four metres."

Here is Strabo's detailed description of this road as it was in the time of Alexander:

"About Phaselis, near the sea, are narrow passes through which Alexander conducted his army. There is a mountain called Climax. It overhangs the sea of Pamphylia, leaving a narrow road along the coast, which in calm weather is not covered with water, and travelers can pass along it, but when the sea is rough, it is in a great measure hidden by the waves. The pass over the mountains is circuitous and steep, but in fair weather persons travel on the road along the shore. Alexander came there when there was a storm, and, trusting generally to fortune, set out before the sea had receded, and the soldiers marched during the whole day up to the middle of the body in water." (Strabo's "Geography," Bohn's transl., Vol. III., p. 48.)

When one reads this clear and definite account, can there be any doubt of a subsidence since Strabo's time? In the campaigns of Alexander the soldiers did not march through more than one metre of water even during a storm; now the water is four metres deep, and if we could conceive the tallest of Alexander's soldiers raised to double height, by one standing on another's head, even the upper one could not keep his head above water. A subsidence therefore is undeniable, for a road would never have been thought of in four metres of water. It cannot be explained by a settlement of the road bed, which is mainly of stone, and gravel, covered with a thin layer of sand deposited by the waves; nor by the shaking down of the base during an earthquake, for such subsidences would be very small, and probably unequal at different points. It can have resulted only from the uniform sinking of the coast by at least three metres. This then is a well authenticated case of subsidence within the historical period.

It is impossible that all of the landslips assumed by Professor Suess to account for the numerous ruins beneath the sea, in Italy, Greece and Asia Minor, can be real; for as a rule such slips would depend on the breadth of the base, and the dip of the underlying strata. Unless the dip is very steep, sliding with a broad base is nearly impossible. Even with abundant underground water, the sliding of a broad mass is very difficult, for there will be rocks or obstructions somewhere which hold it fast. We have already remarked in regard to the mausoleum of Makri that the photograph given by Professor Suess (Vol. II., p. 449) shows that the alluvium is about a mile wide, and very flat. As the adjacent sea seems to be shallow, such a broad mass could not slide into it by the shakings of an earthquake. On the contrary it is clear that the coast sank and carried down the mausoleum with it, so that it is now washed by the tides and waves.

In conclusion we may hold that the Ægean sea probably is rising, and that within recent geological time Asia Minor and Syria have been raised from the sea; so that the Pontus and Caspian were formerly continuations of the Mediterranean, but are now cut off by the secular movement of the earth's crust. Many volcanoes have formerly been active in Asia Minor and Syria, which shows that geologically the region is one of elevation. Lava from beneath the Mediterranean, as well as the Pontus and Caspian, escapes under this region, and in the sinking of the sea bottom the shore is sometimes carried down with it, as in Pamphylia and other places which we have discussed. But in the course of geological ages movement of elevation predominates. Unless this were true, it is highly improbable that the whole region between the Mediterranean, Pontus and Caspian would be so powerfully afflicted by earthquakes.[1]

[1] Since this paper was finished a severe earthquake has occurred at Bitlis in the mountains of Armenia. A press dispatch of April 4, from Constantinople, gives the following report from the Rev. Roy T. Lee, head of the American Mission at Bitlis:

"At ten o'clock in the forenoon of March twenty-ninth there burst upon us unannounced the worst earthquake experienced in forty years in these or the Ezerum volcanic regions. Such was its force that our city seemed to be in the jaws of some monster who would shake us into shreds as some mastiff does his game. Down came the plastering, the furniture was over-

There remains the possibility that the Ægean is being undermined by the expulsion of lava from beneath it, and it might be sinking so long as this process is at work; but it is difficult to doubt that the ultimate destiny of the Ægean is to be raised above the sea and become dry land, thus completing the bridge between Europe and Asia Minor. This general result is indicated by a study of the map. The numerous islands in the Ægean contradict the theory of permanent subsidence. The volcano which used to be active in the island of Lemnos, the eruptions in Eubæa mentioned by Strabo, the elevation of the Island of Delos, the repeated outbreaks near Thera, the numerous small islands which have been reaised in the sea within the historical period,—all these phenomena point to elevatory movement affecting this whole region, because volcanic activity usually shows itself in regions of elevation. It is hardly possible that these several signs of elevation would have appeared if the Aegean were in process of secular subsidence. The activity of Mt. Ararat within historical time, especially in 1840, and of Mt. Demavend, south of the Caspian, and the outbreaks from other volcanoes in Asia Minor, all point in the same direction, and render it probable not only that the region is geologically one of elevation, but also that the Pontus and Caspian were thus cut off from the Mediterranean. The Dead Sea and the valley of the Jordan were cut off in like manner, and by this very earthquake process which has so often afflicted Syria within the period covered by human history.

The mountains in Syria parallel to the Mediterranean east coast, like those in Epirus and Dalmatia so beautifully parallel to the northeast shore of the Adriatic, were as clearly formed by the Mediterranean as the Andes, Rocky Mountains and Sierras were by the Pacific, which for millions of years has been uplifting a hemisphere unknown to the ancients.

As bearing on the subterranean processes at work under the Ægean Sea, by which Olympus and all the surrounding mountains

turned, cracks were opened in strong walls, roofs were shattered and the rain poured in." In this case lava streams were evidently readjusting themselves under the earth's crust. The comparison of the shaking to that which a mastiff gives his game is most appropriate. It was just such shaking that proved so disastrous at San Francisco, Valparaiso, Kingston, and other places where lava was adjusting itself under the crust.

were formed, and repeatedly disturbed by earthshaking Poseidon, the following passages in Homer will not be without interest. The partition of the world among the principal deities is thus explained by Poseidon himself:

"For we are three brothers (descended) from Kronos, whom Rhea brought forth, Zeus and I and Pluto, governing the infernal regions, the third; all things were divided into three parts, and each was alloted his dignity; I in the first place when the lots were shaken was assigned to inhabit forever the hoary sea, and Pluto next obtained the pitchy darkness; and finally Zeus received the wide heavens in the air and the clouds; but the earth is still the common property of all, and lofty Olympus." (Iliad, XV., 187–194.)

The account describing Poseidon's mansions beneath the Ægean sea is as follows:

"Nor did king Poseidon keep a vain watch; for he sat aloft upon the highest summit of the woody Thracian Samos, admiring the war and the battle. For from thence all Ida was visible, and the city of Priam was visible, and the ships of the Greeks. Then coming out of the sea, he sat down, and he pitied the Greeks, subdued by the Trojans, and was very indignant with Jove. But presently he descended down from the rugged mountains, rapidly advancing on foot, and the high hills and woods trembled beneath the immortal feet of Poseidon, advancing. Thrice indeed he strode, advancing, and with the fourth step he reached Ægæ, his destined goal. There distinguished mansions, golden, glittering, ever incorruptible, were erected to him in the depths of the sea. Coming thither, he yoked beneath his chariot the brazen footed steeds, swiftly flying, crested with golden manes. But he himself placed gold about his person, took his golden lash, well wrought, and ascended his chariot. He proceeded to drive over the billows and the monsters of the deep sported beneath him on all sides from their recesses, nor were ignorant of their king. For joy the sea separated; and they flew very rapidly, nor was the brazen axle moist beneath. And his well-bounding steeds bore him to the ships of the Greeks.

"Now there is an ample cave in the recesses of the deep sea, between Tenedos and rugged Imbrus. There earthshaking Poseidon stopped his horses, loosing them from the chariot and cast beside (them) ambrosial fodder to eat." (Iliad, XIII., 10–35; Buckley's Translation.)

The Ægean Sea was the part of the Mediterranean with which Homer was best acquainted, yet he possessed fairly accurate knowledge of many seas and many lands; and the fact that out of all this domain of ocean he placed Poseidon's chief abode beneath the Ægean indicates that if he did not possess divine wisdom, with regard to earthquake forces, he at least chose for the earthshaker's dominions the very spot which would be selected to-day, in the light of the history of thirty centuries since the composition of the Iliad.

VI. Conclusions.

It now remains to sum up very briefly the chief conclusions at which we have arrived. Different arguments appeal with unequal force to different minds, and doubtless there are some who will hesitate at departing from the views recently current in the sciences which deal with the earth. Others who have more or less despaired of definite results under the uncertainty and confusion heretofore existing, will naturally be slow to believe that the laws and order of nature are so simple. But these varieties of temperament will not change the force of the several arguments for a single cause shown to underly the most varied phenomena.

We have endeavored to show not only that the cause assigned in the paper on earthquakes is adequate to account for the observed phenomena, but also, through the process of exclusion, that no other possible cause is at work in world-shaking earthquakes. In this survey of the whole field we were led to reject the theory of contraction and secular cooling as an effective agency in modifying the surface of the earth. And we contrasted the absence of world-shaking earthquakes in an inland region like Colorado and Kansas or the Desert of Sahara with their constant occurrence along the Andes, as a proof that the forces involved depend on the ocean and not at all on secular cooling. For if this latter is a real cause it should be at work inland as well as along the sea coasts. These considerations therefore seem to establish the cause which has formed mountains, and wrinkled the earth's crust in a very complicated manner.

In the study of this question consideration was carefully restricted to earthquakes of the world-shaking class, because the great disturbances were held to be best adapted to disclosing the true nature of the processes hidden beneath the earth's surface. The problem was thus simplified and cleared of the confusion that would necessarily have resulted from the simultaneous consideration of all earthquakes, both large and small.[1] The slight shocks may be due to various

[1] Viewing the earth as an elastic solid under stresses of varying intensity several eminent mathematical physicists have recently considered the dilatational stability, or the stability of the crust under its own gravitation, when some of the surface matter is removed. After calculating these hypothetical effects by elegant mathematical methods, some of them have inferred that when denudation takes place under geological agencies, thus

causes, but are mainly traceable to the effects of great earthquakes of the present and past, which have left the earth's crust much broken and distorted and often in an unstable condition.

This is clearly shown by the after-shocks which follow world-shaking earthquakes in great numbers and for a long time. Thus nearly all earthquakes result directly or indirectly from the great earthquakes; but the movement in different cases is doubtless very different, and consists largely in the gradual adjustment of the disturbed crust. Hence our principal conclusions are the following:

1. The cause of world-shaking earthquakes, mountain formation, and kindred phenomena connected with the physics of the earth, is the secular leakage of the ocean bottoms, which gives rise to the development of steam beneath the earth's crust.

2. This vapor and no other is the cause of these disturbances, because if any other vapor were at work beneath the crust some of it would escape through the vents of volcanoes, and become recognizable by observation.

lowering the level, the crust, having the weight at length removed, would spring upward, perhaps recovering much or all of the elevation lost by denudation. The following considerations will show that this reasoning as applied to geology is likely to be fallacious. Under ordinary conditions denudation is very slow, and the unloading too gradual to produce anything but the most insensible relief upward. We can see that this will be true by considering how little a corresponding increase of load would sag the level. If for example the load be a mass of soil or of rock 100 feet deep, the sagging where the ground is hard, but not solid rock, would be of the order of a few inches. The removal of such a load would no doubt give rise to a similar restitution upward, but no more; and as such denudation in nature is excessively slow, the springing upward is infinitesimal, and requires nearly infinite time. Therefore no important geological effects depend on such causes, though perhaps insensible surface movements may thus arise. But they would scarcely claim the title of microseisms and certainly could not rise to the dignity of earthquakes; for even if landslides should occasionally develop in this way the resulting shocks would be mere local tremors. No heavy earthquakes could depend on such causes, for if so they should be observed far inland as well as along the sea coast, which is contrary to observation. Accordingly while such reasoning is learned, and mathematically interesting, it has only a slight physical basis, and as applied to geology is deceptive and misleading. Until the true cause of world shaking earthquakes is placed beyond doubt and fully recognized, the consideration of such infinitesimal influences as this had better be passed over, because it simply bewilders the subject. In this connection particular attention is called to the footnote on pp. 408–409 of the paper on the cause of earthquakes.

3. The distribution of volcanoes, mountains, and earthquakes shows that all these phenomena depend upon the sea and water generally; wherefore the depth of earthquakes is shallow and so far as is known never exceeds forty miles.

4. The principal purpose of earthquakes is the elevation of land, which has made possible the development of the higher forms of life upon the earth.

5. Plato, Aristotle, Strabo and Pliny all held that water and air penetrate into the earth, through hollows, fissures and crevices, thus developing vapor in the heated interior, a part of which is expelled from volcanoes. And they also held that earthquakes are due to the tension of elastic vapors seeking to escape and diffuse themselves in the atmosphere, whether these vapors break through and form eruptions, or remains hidden in the earth.

6. The movement of streams of lava beneath the earth's crust, which occurs in every world-shaking earthquake, is the modern view of Plato's Pyriphlegethon. Though Aristotle and his successors associated earthquakes with the sea, they do not appear to have held any definite theory of the movement of the fluid beneath the earth's crust. From Strabo's remarks, however, it appears probable that they considered mountains to be formed by earthquakes and eruptions.

7. Aristotle correctly associated seismic sea waves with earthquakes; and even Homer assigned these great disturbances of the sea to Poseidon's trident, which was also the means employed for raising up islands from the bottom.

8. The withdrawal of the water from the shore after an earthquake and its return as a great wave, was familiar to Aristotle, and is implied in his description of the sinking of Helike in 373 B.C.

9. This pathetic calamity was due to the subsidence of a portion of the sea bottom in the gulf of Corinth, after lava had been expelled from beneath it, and pushed under the mountains of Arcadia.

10. The elevation and subsidence of the land long ago contended for by Strabo is now proved to occur, and examples of this movement may be cited in ancient as well as in modern times. While Strabo clearly states the fact of such movement he seems to have been doubtful of the cause. Aristotle does not give the cause of these changes,

though he no doubt associated them with earthquakes and the sea, which seems to be the view also of Plato, so far as one can judge from his description of the sinking of Atlantis.

11. The theory here developed was therefore roughly outlined and more or less anticipated by the leading Greek philosophers, especially by Aristotle; and as formulated by them it continued to be held till modern times, though of late years it has been quite abandoned, owing to the unfortunate development of the theory of tectonic earthquakes.

12. In the present paper we have examined carefully the question of the temperature of the earth, and have given what appears to be the most probable law of its internal distribution.[1] No external effects traceable to deep-seated movements of heat are discoverable, and we have therefore concluded that the nucleus of the globe is now and always has been quiescent.

13. The deformations of the earth's surface are found to be due to earthquake processes working just beneath the crust, and to original inequalities of the surface dating from the genesis of the moon, which gave rise to the principal ocean basins.

14. The two methods for estimating the period since the consolidation of the globe agree in indicating that it was of the order of ten million years, and thus by no means so long as many geologists have been inclined to believe. Moreover, appreciable cooling has not extended below the depth of some forty miles, or one one-hundredth of the radius, so that it is confined almost wholly to the crust.

15. It is estimated that the Andes might be formed in something like three million years, and the plateaus west of the Rocky Mountains in not more than five million years.

16. When the tension of the imprisoned steam under the oceans becomes very great, it finally causes the crust to yield along the margins, and mountains are pushed up where the crust breaks parallel to the coast. When an avenue of escape is thus once opened for the lava, it continues active, and the mountains grow higher and higher, unless meanwhile the sea recedes to too great a distance.

[1] A comparison of the small figure in the right hand upper corner of the diagram with the larger figure F shows how one of the distributions of temperature passes into the other by continuous flow of the heat outward while the planet is consolidating. The monatomic curve thus becomes an ellipse.

17. At one time or another the principal oceans form mountains all around them, but in any one geological age the relief may be chiefly on one side, except when the ocean is of very great extent, like the Pacific,[1] which therefore is active all around, and obtains some internal relief by the formation of numerous islands.

18. We have shown that just as soon as the exploding lava acquires sufficient tension or elastic pressure to lift the crust along a fault line, a displacement occurs there, and the lava spreads beneath the block thus moved, giving relief along the path of least resistance. It is the enforced movement of these subterranean lava streams which shakes down cities and devastates whole countries.

19. It is found that secular cooling is so very slow and so small in amount that it has no sensible effect on the physics of the globe. Accordingly it is shown that the earth is not now shrinking, nor has it been at any time since the consolidation began.

20. On the contrary the formation of pumice everywhere beneath the land, as it is elevated by the steam forming under the oceans, is raising the level of the continents, in spite of erosion. And as the oceans are being gradually narrowed by the recession of the sea, after successive mountain chains are formed—some of the water sinking beneath the earth's crust, and the rest collecting into a smaller area, here and there growing deeper when lava is expelled from beneath the margins—it may well be that the ocean level is nearly stationary, or rising slightly with respect to the centre of the earth, though there is a secular lowering of the strand line relatively to the land. Accordingly so far from contracting the earth may be in reality very slightly expanding. This secular expansion is due to the formation of pumice nearly everywhere beneath the crust.

[1] In his *Manual of Geology,* 1863, the late Professor J. D. Dana came surprisingly near many of the views reached in the present investigation. He pointed out with great clearness that the continents not only are built on one model, with the mountains around their borders, while the interior is a depressed basin, but also that the highest border is on the side of the greatest ocean, and conversely. In speaking of this fundamental law he remarks that "the relation between the extent of the oceans and the height and volcanic action, etc., of their borders proves that the amount of force in action had some relation to the size and depth of the ocean basin. The Pacific exhibits its greatness in the lofty mountains and volcanoes which begirt it."

21. The calculated fall of temperature for the whole earth of 10° C. (Tait) and of 45° C. (Daniell) in 100 million years, with the cubical coefficient of expansion of 0.00002, found by experiment for average rock of the earth's crust, would produce a shrinkage of only 0.26 and 1.16 miles respectively. But if the period since the earth's consolidation be only about one tenth that here assumed, according to the usage of geologists, the corresponding contraction would certainly not much exceed one tenth of these values, or say 137 and 612 feet. These values are so very small that the uplifts due to earthquakes might easily cause the globe to expand rather than contract. Accordingly if our present data do not enable us to conclude that the earth is undergoing secular expansion, we may at least conclude that it certainly is not sensibly contracting. Its dimensions seem to have been nearly stationary since the consolidation began.

22. The principal phenomenon heretofore requiring the theory of contraction is the formation of mountains; but Rev. O. Fisher has shown that this cause is quite inadequate, and in the paper on the cause of earthquakes we have developed the theory of mountain formation depending on the sea. The doctrine of the secular contraction of the globe must therefore be entirely abandoned, and the explanation of the phenomena sought in other causes.

23. By the existence of unstable pinnacles of rock formed by the gradual processes of geological time it seems to be proved that no deep and very powerful convulsions of our globe, except the ordinary shocks noticed in earthquakes, have taken place in many millions of years. We must therefore ascribe to ordinary world-shaking earthquakes the highest geological significance. These forces depending on the sea produce both elevations and depressions of the land, and explain all the phenomena of movement witnessed upon the earth.

24. In the development of these views Aristotle and Strabo occupy the foremost places among the ancients; Humboldt, Lyell and Darwin among the moderns; while Fourier and Lord Kelvin naturally claim the leading places among the illustrious physicists who have occupied themselves with these great problems of the heat of our planet.

Blue Ridge on Loutre,
Montgomery City, Missouri, March 22, 1907.

In conclusion it remains[1] to notice one difficulty which has occurred to some readers, and thus should perhaps be given further elucidation. By those who have not made a careful study of the porosity of matter under great fluid pressure, it seems to be felt that notwithstanding the apparently conclusive character of Daubrée's experiments, they form a rather slender experimental basis upon which to build a satisfactory explanation of the sinking of sea water through the earth's crust, which is composed of from ten to twenty miles of solid rock like granite. That this supposed difficulty is devoid of real foundation will appear from the following considerations, which enable us to show that the oceans do experience such a secular leakage, and to prove this fact quite independently of Daubrée's experiments.

1. In the paper on the cause of earthquakes, § 15, it is shown that the chances are at least (100 billion)^6 or a decillion decillions to one, that the mountains are formed parallel to the shore by a true physical cause depending on the oceans. This is of course an absolute certainty. The mountains therefore depend in some way upon the sea. To perceive most clearly what this dependence is, we may notice, as in the former paper, that the elevation of the Andes has been accompanied by the sinking of the adjacent sea bottom into a parallel trough of about the same volume. That lava has been expelled from beneath the sea and pushed up under the land is indicated by the depression in the sea bottom parallel to the Andean Cordillera; and this inference drawn from the geometrical evidence of the surface of the lithosphere is confirmed by direct observations, made within the historical period, on those earthquakes which produce sensible uplifts of the coast and simultaneous subsidences of the sea bottom, as shown by the accompanying seismic sea waves. Moreover unbroken continuity between the small uplifts and subsidences observed within the historical period and the vastly greater movements gradually accumulated during past geological ages is established by the deposits of shells and fossil beds found at great heights in the Andes, and by the deep depressions in the adjacent oceanic trough. It is therefore undeniable that in the course of long ages

[1] This closing discussion, with the exception of the last sentence, was added April 18, 1907.

the mountains and coast have been greatly elevated and the adjacent sea bottom correspondingly sunk down.

2. The earthquake shocks producing these effects are found to occur at a depth of some 15 miles, where the pressure is so great that no cavities in the earth can possibly exist. Therefore there are neither voids at this depth beneath the mountains nor corresponding increases of density beneath the sea where the bottom has subsided, but vast quantities of matter have been expelled from beneath the ocean and pushed up under the adjacent mountains. These phenomena, as observed in South America, are clear and indisputable, and admit of but one interpretation: namely, that the Andes have been formed by successive earthquakes which have expelled the lava from beneath the bed of the adjacent sea, and thus upraised the crust into some of the mightiest mountains of the globe.

3. The next question then becomes: How is the lava expelled from under the sea? We say lava rather than solid rock, because owing to the increase of underground temperature, at a depth of 15 to 20 miles below the surface, where the world-shaking earthquakes originate, the matter must be essentially molten, in spite of the great pressure to which it is subjected. We therefore answer that since the earth is neither contracting nor experiencing any other sensible changes from secular cooling, the expulsion can be accomplished only by explosive vapors such as are emitted from the neighboring volcanoes, which often break out into eruption simultaneously with an earthquake noticed to produce an elevation of the shore and a sinking of the sea bottom. This vapor therefore can be nothing else than common steam.

4. Now the steam developing beneath the earth's crust and producing earthquakes and volcanic activity can be traced to but two possible sources: First, the original magma of the globe, which, in default of a better explanation, has been frequently invoked by the geologist; Second, the secular leakage of the ocean bottoms effected through 15 miles of solid rock like granite, which naturally appeals to the physicist. If the escaping steam, or any sensible part of it, came from the central magma of the globe, volcanoes and earthquakes necessarily would occur in the interior of continents as well as along the coasts, on islands, and in the depths of the sea. For

the continents are large areas, and altogether cover more than one fourth of the total surface of the globe; yet the volcanoes and world shaking earthquakes are confined to the neighborhood of the oceans or other large bodies of water.

5. It clearly follows therefore that the agitating vapor does not come from the central magma of the globe, but must come from the secular leakage of the ocean bottoms. This is unmistakably indicated by the most overwhelming evidence of nature.[1]

[1] Newton's rules of reasoning in natural philosophy should be borne in mind here:

RULE I. "*We are to admit no more causes of natural things, than such as are both true and sufficient to explain their appearances.*"

"To this purpose the philosophers say, that Nature does nothing in vain, and more is in vain, when less will serve; for Nature is pleased with simplicity and affects not the pomp of superfluous causes."

RULE II. "*Therefore to the same natural effects we must, so far as possible, assign the same causes.*"

"As to respiration in a man, and in a breast; the descent of stones in Europe and in America; the light of our culinary fire and of the sun; the reflection of light in the earth, and in the planets."

RULE III. "*The qualities of bodies, which admit neither intension nor remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies whatsoever.*"

Newton's explanation of this rule is too long to be quoted here; but it is worthy of the most careful study.

RULE IV. "*In experimental philosophy we are to look upon propositions collected by general induction from phenomena as accurately or very nearly true, notwithstanding any contrary hypotheses that may be imagined, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions.*"

"This rule we must follow that the argument of induction may not be evaded by hypotheses."

In the investigation of the physics of the earth involving many hypotheses of very unequal weight this last rule acquires special importance. If therefore some trifling details are not yet explained or understood we must not on that account reject the cause gathered by a general induction of all the related phenomena of the globe. On the contrary we must adhere to the cause "as accurately or very nearly true, notwithstanding any contrary hypotheses that may be imagined, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions," in order that the "argument of induction may not be evaded by hypotheses." In his explanations of Rule III. Newton remarks: "We certainly are not to relinquish the evidence of experiments for the sake of dreams and vain fictions of our own devising; nor are we to recede from the analogy of Nature which uses to be simple, and always consonant to itself."

6. Therefore it incontestably follows that the explosive vapor operating in earthquakes, volcanoes, mountain formation and kindred phenomena connected with the physics of the globe, comes from the secular leakage of the ocean bottoms, effected through the earth's crust, composed of some fifteen miles of solid rock like granite.

7. Accordingly it necessarily follows also that Daubrée's experiments are applicable to layers of rock twenty miles thick, when the water is subjected to the great fluid pressure constantly operating in the deepest oceans. Our fundamental proposition is thus proved quite independently of Daubrée's experiments. In fact by simply observing the phenomena of nature one might infer that such experiments as those made by Daubrée would be possible under good laboratory conditions.

8. In the case of our thinly encrusted planet so largely covered with water the natural arrangement between the overlying oceans and the underlying molten globe constitutes a laboratory of the most imposing magnitude, infinitely transcending anything ever conceived by man, with gigantic experiments constantly going on. All that is needed therefore is for the philosopher to interpret nature's stupendous operations, which unfortunately only too often prove disastrous to human life, because of our ignorance and disregard of natural laws. The highest duty of the philosopher is to discover these laws and make them available to the world, so as to contribute as much as possible to the repose and safety of mankind.

9. According to the theory here developed earthquakes and related phenomena, which have so afflicted the world from the earliest ages, are not much to be dreaded when their laws are understood, and adequate precautions are taken to secure the building of safe houses. When, however, people live near active volcanoes protection is not always possible, though fortunately it is generally within reach at most places visited by earthquakes throughout the world.

10. But as great multitudes of people live in cities by the sea they are also subjected to the dangers arising from seismic sea waves; yet if a place of refuge exists they usually have ample time to escape. And even the ships in the harbor will generally be safe if they promptly put to sea on the first sign of the withdrawal of the

water after the earthquake, which always indicates that the sea bottom has sunk. Thus by the study of the laws of the physical world, and the diffusion of the resulting useful knowledge, a great measure of safety may be secured from some of the most dreadful forces in nature, and in the course of time the interests of civilization enormously conserved.

When we reflect over these results and contemplate the harmony thus established in many branches of the physical sciences, is it not obvious that Newton's belief that the great laws of nature are simple may with great advantage still be borne in mind by those who wish to arrive at the ultimate causes which lie at the basis of natural philosophy?

BLUE RIDGE ON LOUTRE,
MONTGOMERY CITY, MISSOURI, April 18, 1907.

ADDENDUM.

Further Considerations on the Earthquake at Helike and Bura, 373 B. C.

Some time after the foregoing was finished it occurred to me to consult Grote's "History of Greece," in the hope of obtaining further light on the famous disaster at Helike; and from his references (Vol. X., p. 157) to Diodorus Siculus, Ælianus and Pausanias I have prepared the following addendum:

1. *Diodorus Siculus, Book XV., Chap. V.*—It is well established that this historian flourished in the reign of Augustus, but the date of his death is not known. The translation here followed is that of G. Booth, London, 1700. This is an old work, and the style of writing is antiquated, but the meaning appears to be clear.

"Afterwards when Asteius was chief magistrate at Athens, and six Military Tribunes, viz. Marcus Furius, Lucius Furius, Aulus Posthumus, Lucius Lucretius, Marcus Fabius and Lucius Posthumus executed the office of Consuls at Rome, there happened such dreadful earthquakes and inundations in Peloponnesus (throughout all the cities and over all the country) that are incredible to relate. For never in any former Ages did the like calamity fall upon the Grecian Cities, which were now swallow'd up together with their inhabitants; and certainly some Divine Power contrived and executed this remarkable ruine and destruction of Mankind: Nay the time when it was done aggravated the greatness of the calamity. For the earthquake hapned not in the day (when the distressed might have found out some way or other to have helped themselves) but in the night; and

when the houses by violence of the shake fell down in confused heaps; so that (by the darkness of the night and the suddenness of the ruine) men were in that perplexity that they knew not which way to turn themselves for security; in so much as the greatest part of the inhabitants (buried in the rubbish of the houses) miserably perished. But as soon as it was day some came running out of the houses, and thinking they had escaped the danger, fell into a far greater and unexpected mischief; for the sea raged to that degree, and broke in with that violence that it swallowed up them and their houses together. Two cities of Achaia, one called Helica and the other Bura, chiefly suffered by this sad accident, of which two Helica was of the greatest account of any of the cities of Achaia.

"There was a very hot dispute concerning the cause of this evil. Indeed the natural philosophers do generally ascribe all such events to Natural Causes, and necessary circumstances, and not to any Divine Hand; But they who have more reverend thoughts and sentiments of a Deity, give a very probable account of this matter, that this destruction was the effect of the Anger of the Gods, for the impious violation of the rights of Religion, of which we shall give a more particular account. . . ."

After describing the impious conduct of the Heliconians, Diodorus continues:

"Upon this they of Helica siezed upon all the goods of the Ionians and committed the Ambassadors to Prison, and so carried it very impiously towards the Deity. Therefore they say Neptune being angry, to revenge himself upon their impiety (by this earthquake and inundation of the sea) brought this grievous calamity upon those cities. And that it was done by him they use this for an argument: *That it is generally believed that this God hath the power of inundations and earthquakes in his own hands;* and that *Peloponnesus* had been ever reputed the Habitation of *Neptune,* and the country dedicated to him and that all the Peloponnesian cities worshipped this God above all others. Besides this, they give a further reason of said accident. There are (as they say) in Peloponnesus great cavities underground, which by the sea flowing here and there through the earth are turned into great Ponds and Lakes of water. And indeed it is very certain that there are two rivers in that Peninsula, which apparently fall into the caverns of the earth. For the Rivers which ran by Pheneum in former Ages sank in one place into the earth, and became invisible, being swallowed in these caverns underground. Another was lost at a great opening of the earth at Stymphius, and ran unseen underground for the space of two hundred stages, and rose again near the city Argos." (Diodorus Siculus, Lib. XV., Cap. V., translated by G. Booth, London, 1700.)

2. *Ælianus, De Natura Animalium.*—This well known author probably flourished in the time of the Emperor Hadrian. His account of the earthquake at Helike is short but very clear. As given in Teubner's edition of the works of Ælianus, Leipzig, 1864, the account (xl., 19) runs thus:[1]

[1] Rev. Theodore F. Burnham very kindly verified the translation now offered.

"When a house obviously is about to be overthrown, the mice which are in it leave along with the weasels, and they anticipate the disaster and emigrate. This indeed they say took place also in Helike. For when the Heliconians were engaged in religious worship, upon the arrival of the Ionians, they sacrificed them (the animals) upon the altar, whence forthwith (this is Homeric) certain gods manifested signs unto them; for five days before the disappearance of Helike all the mice that were in it, and weasels and serpents, millipedes and beetles and the rest of things of this kind, crept forth together into the road leading to Cerynea. And the Heliconians seeing what had happened marveled indeed, but were unable to understand the cause. And when the aforementioned animals had left the place, an earthquake occurred in the night, and the city collapsed, and, overflown by a great wave, Helike disappeared; and by chance ten vessels of the Lacedemonians lying at anchor perished in the rush of the waters. And it came to pass necessarily in respect to the vengeance upon the rowers of the impious men, that justice demanded their lives. And in proof of this judgment, Pantocles, the Lacedemonian, having set forth to go through Sparta to reach those absent from the force with Dionysus who were in Cythera, when he had seated himself on the bench of the Ephors, was torn to pieces by dogs."

3. *Pausanias, Description of Greece, Book VII., Caps. XXIV.–XXV.*—It is well known that this famous traveler lived in the time of the Antonines, and probably finished his work in the reign of the Emperor Marcus Aurelius, about 170 A. D. A very excellent translation with critical introduction and copious commentary, the whole in six volumes, has recently been published by J. G. Frazer, M.A., LL.D. (Glasgow), fellow of Trinity College, Cambridge (MacMillan & Co., London, 1898). The following accounts of the destruction of Helike and Bura are taken from Frazer's translation.

In the description of Achaia, Book VII., Chap XXIV. (pp. 365–366) Pausanias says:

"Going on you come to the river Selinus, and forty furlongs from Ægium is a place Helice on the coast. Here there used to be a city Helice, and here the Ionians had a most holy sanctuary of Heliconian Poseidon. Their reverence for that god has survived to the present day, in spite of their expulsion by the Achæans and their migration first to Athens, and afterwards to the coast of Asia. At Miletus, on the way to the spring of Biblis, there too is an altar of Heliconian Zeus in front of the city; and in Teos, too, the Heliconian god has an enclosure and an altar which are worth seeing. Homer also refers to Helice and Heliconian Poseidon. 5. But in after time the Achæans of Helice forced some suppliants from the sanctuary, and put them to death. The wrath of Poseidon did not tarry. The land was instantly visited by an earthquake, which swallowed up not only the buildings, but the very ground on which the city had stood. Ominous signs, vouchsafed by the god, foretell the approach of great and far-reach-

ing earthquakes. The nature of the sign is generally the same. For earthquakes are preceded either by heavy and continuous rains or long droughts. The weather, too, is unseasonable. If it is winter, the weather is sultry; if it is summer, there is haze, and the sun's disc appears of an unusual colour, slightly inclining either to red or dun. Springs of water mostly dry up. Sudden gusts sometimes sweep across the country, blowing the trees down. At times, too, the sky is shot with sheets of flame. Stars are seen of an aspect never before known, and strike consternation into beholders. Moreover, a mighty murmur is heard of winds blowing underground. And many more signs there are whereby the god gives warning of the approach of violent earthquakes. The character of the shock itself is not always the same. The original observers and persons instructed by them have been able to distinguish the following classes of earthquakes. The mildest form of earthquake—if so dire a calamity can be thought to admit of alleviation—is when the first shock which levels the buildings with the ground, is counteracted by an opposite shock which raises up what the first had knocked down. In this kind of earthquake you may see columns, which had been all but hurled from their bases, rising to the perpendicular, and walls which had been cracked closing up again; and beams, which the shock had caused to slide out, return to their places, and similarly rifts made in conduits and water-channels are cemented better than they could have been by a craftsman. The second kind of earthquake destroys everything that is the least unsteady; whatever it strikes it instantly overthrows, as with the blow of a battering ram. The deadliest kind of an earthquake is illustrated by the following comparison. In an unintermitting fever a man's breathing is quick and laboured, as is shown by symptoms at various points of the body, but especially at the wrists; and they say that in the same way the earthquake dives under buildings and upheaves their foundations, just as molehills are pushed up from the bowels of the earth. It is this kind of shock alone that leaves not a trace of human habitation behind. They say that the earthquake at Helice was of this last kind, the kind that levels with the ground; and that, besides the earthquake, another disaster befell the doomed city in the winter-time. The sea advanced far over the land and submerged the whole of Helice, and in the grove of Poseidon the water was so deep that only the tops of trees were visible. So that between the suddenness of the earthquake and the simultaneous rush of the sea, the billows sucked down Helice and every soul in the place. 7. A like fate befell a city on Mount Sipylus; it disappeared into a chasm, and from the fissure in the mountain water gushed forth, and the chasm became a lake named Saloe. The ruins of the city could still be seen in the lake until the water of the torrent covered them up. The ruins of Helice are also visible, but not so clearly as before, for they have been eaten away by the brine."

Again in Chapter XXV. (p. 367) these additional remarks are added:

"The Lacedæmonians also slew men who had taken refuge in the sanctuary of Poseidon at Tænarum; and not long afterward their city was shaken by so prolonged and severe an earthquake, that not a house in Lacedæmon stood the shock.

"2. The destruction of Helice took place when Astius was archon at Athens, in the fourth year of the hundred and first Olympiad, in which Damon of Thurii was victorious for the first time. As none of the inhabitants survived, the territory now belongs to Ægium. . . .

"5. Returning from Cerynea to the high road, and proceeding a little way along it, we turn off a second time from the sea to the right in order to reach Bura. The town stands on a mountain. They gave it the name of a woman, Bura, whose father was Ion, son of Xuthus, and whose mother was Helice. When the god blotted out Helice from among men, Bura also was overtaken by a severe earthquake which spared not even the ancient images in the sanctuaries. Such people as chanced at the time to be away at the wars or on other business were the only survivors, and they rebuilt Bura. There is here a temple of Demeter, another of Aphrodite and Dionysus, and another of Illithyia. The images are of Pentelic marble, and are works of Eluclides, an Anthenian. The image of Demeter is clothed. There is also a sanctuary of Isis.

"Having descended from Bura in the direction of the sea, we come to a river named Buraicus and to a small image of Hercules in a grotto. This image is also surnamed Buraicus, and there is a mode of divination by means of dice and a tablet. The person who inquires of the god prays before the image, and after praying he takes four dice and throws them on the table. Each die has a certain figure marked on it, and the meaning of each figure is explained on the tablet.

"The straight road from Helice to the Hercules is about thirty furlongs. Going on from the Hercules you come to the mouth of a river which comes down from a mountain in Arcadia, and never dries up. The river is called the Crathis, and Crathis, too, is the name of the mountain which are its springs. From this Crathis the river beside Crotona in Italy got its name. On the bank of the Achæan Crathis once stood the city of Ægæ; they say that in course of time it was deserted by its inhabitants, because they were a feeble folk."

In his excellent and lucid commentary on Pausanias' "Description of Greece," Frazer says of *Bura:*

"Between the Bouphousia (Cerynites) and Kalavryta (Buraicus) rivers there rises a massive hill, which falls away on the south and west in a line of stupendous precipices. This is the hill or mountain of Bura; it is now called by the natives *Idra.* On the north the hill is separated from the sea by a strip of level coast land; on the southern side it is connected by a neck or saddle (which is, however, far below the summit of the hill) with the loftier mountains which begin here and stretch away into Arcadia. On this neck or saddle are the remains of Bura. They consist of extensive, though insignificant, remains of walls and foundations, spread along the southern part of the western foot of the hill as far as the copious spring which gushes from the bottom of the precipice. Among the ruins is a chapel of St. Constantine, which presumably occupies the site of an ancient sanctuary. Mixed with the ruins are huge blocks of rock which appear to have been hurled from the beetling crag above by an earthquake, perhaps the same earthquake which destroyed the city.

"The whole neighborhood gives one the impression that it has been subjected to gigantic convulsions of nature. The crags tower up to dizzy heights above the traveler, and the rivers find their way through tremendous gorges to the sea.

"At the southwestern foot of the hill of Bura, where the precipices rise highest, lie the ruins of the ancient theatre, with remains of fifteen rows of seats; the orchestra is about 32 paces broad. From some of the seats there is a fine view of the Corinthian Gulf, with the mountains of northern Greece rising behind it. A few remains of the town wall may be seen below the theatre.

"The citadel of Bura probably occupied the summit of the hill. The western face of the hill is a sheer wall of rock; a single path here leads to the summit."

From this account it is clear that most of the site of Bura is too high above the sea to have been inundated by the seismic sea wave of 373 B. C., and that the damage was due principally to the violent shocks during that dreadful earthquake. Pausanias says that it was so violent "that it spared not even the ancient images in the sanctuaries. Such of the people as chanced to be away at the wars or on other business were the only survivors, and they rebuilt Bura." This accords well with descriptions of the yawning chasms at Bura given by Aristotle, Lucretius and other writers.

It also appears that according to the authorities available to Pausanias, Helike subsided so much that only the tops of the trees in the grove about the temple of Poseidon remained above the water. As this temple could not well have been less than fifty feet above sea level, the total subsidence must have been about a hundred feet. This effectively disposes once for all of the claims of Professor Suess and others that it was caused by the breaking loose of alluvium from the older geological formations. It is therefore placed beyond doubt that under the throes of the earthquake the bed of the Gulf of Corinth gave down and thus brought on the most famous inundation of antiquity.

There seems to have been many earthquakes that year (373 B. C.), but unfortunately our accounts are too uncertain to enable us to fix upon the exact order of events. But as Pausanias says that "besides the earthquake another disaster befell the doomed city in the winter-time," we may safely infer that in all probability the sinking of the sea bottom took place with one of the later shocks, as sometimes happens in South America. This agrees also with the

somewhat vague language of Diodorus Siculus, who says that the sea wave occurred in the day following the earthquake at night. None of these accounts are to be too implicitly trusted, because Pausanias says no one at Helike escaped, while Diodorus implies that some persons were escaping when the wave overwhelmed the city.

If there had been a series of slight but incessant earthquake shocks previous to the terrible earthquake at night, the account given by Ælianus of the exodus of mice, weasels, and other animals from the town becomes very intelligible; but here again we must beware of reposing too much confidence in narratives composed after the lapse of several centuries. Of all the contemporaries of this event, Aristotle was best qualified to speak with authority; but, as we have seen, his account gives only the leading facts without the details added by later writers, and is impossible to estimate how many of these details are authentic.

On the whole it appears to be certain that there were many premonitory signs of the disaster, in the form of a series of preliminary shocks extending through several months and felt all over the Peloponnesus; and it seems equally certain that the greatest shock occurred in the night. This leveled Helike and Bura to the ground, and was due to the expulsion from beneath the bed of the sea of a mass of lava which was pushed under the mountains in Arcadia, causing great chasms to open near Bura. In consequence of this undermining of the sea bottom it afterwards gave down nearly a hundred feet, but we cannot be sure whether the subsidence took place with the great shock in the night, or followed from one of the violent aftershocks the next day. On the whole the latter view seems the most probable, since there is no reason why the sea bottom once undermined might not sink with one of the violent after shocks which always follow great earthquakes.

When we consider the interval of time by which we are removed from this great disaster, it is quite remarkable that our knowledge of it should be so complete as it is. Plato was then in his fifty-fourth year, at the height of his powers, and at the head of the Academy in Athens, and Aristotle was a boy eleven years old; but the impression made upon contemporary Greek thought was proportionate

to what might have been expected from the sudden obliteration of Helike, at once the most important city in Achaia, and the center of the Panionian league, owing to the prosperity and increasing prestige it had enjoyed since the days of Homer. As Aristotle tries to account for the disaster by the theory of opposing winds, it is evident that it must have been a subject of keen speculation among the leading Greek philosophers. Although the explanation given by Aristotle is now invalidated by the advancement of science, he was entirely correct in ascribing this dreadful calamity to the agitation of vapors confined within the earth, which in seeking release finally brought on the cataclysm.

There are few results in science of deeper interest than those obtained by a principle which enables us to remount to the earliest ages of history, and to explain phenomena contemporaneously observed by the greatest minds of antiquity. This impressively illustrates the difference between a discovery disclosing a true physical cause and an effort directed to the mere observation of phenomena. A *vera causa* explains with equal facility the phenomena of every country and the observations of every age, whereas without it we can not correctly understand the commonest phenomena witnessed in our own time.

April 30, 1907.

Final Note.

Since the above discussion was completed, the writer has been much impressed with the excellent maps of the ocean depths published by the U. S. Coast and Geodetic Survey (Physical Hydrography, Manual of Tides, Part IV A, by Rollin A. Harris, Appendix 7, Report for 1900). The reader is requested to study especially maps 19 and 20, of this appendix, and to notice how the earthquake belts of the world as laid down by Milne follow the deep trenches in the sea. The borders of the North Pacific ocean, about Alaska, the Aleutian and Kurile Islands, and Japan are literally surrounded by these deep, narrow trenches, running right through the centres of the great earthquake belts of the globe. As these trenches are very long, narrow, and deep, and at the same time exactly paralleled by chains of islands rising out of the sea, which are mountain ranges under water, we see at once the true cause of earthquakes. The

expulsion of lava from under these trenches has raised the adjacent ridges, and when thus undermined the sea bottom has sunk down. This may be inferred with entire confidence and certainty not only from the relative situation of the trenches and adjacent ridges, but also from the great earthquakes and accompanying seismic sea waves observed in these regions within historical times. No other interpretation of the phenomena than the one we have given is really possible. If, however, any one should still cling to the old theory that the shrinkage of the earth is an effective cause in modifying the surface of our globe, let him explain why the shrinkage should take place in these long narrow trenches and be accompanied by the elevation of adjacent ridges. The elevation of the ridge shows that matter is pushed under it, and the sinking of the bed of the adjacent trench shows that the sea bottom is undermined. It therefore incontestably follows that lava is expelled from under the trench and pushed under the adjacent crust, upheaving it into the form of a ridge. Thus mountain ranges are formed in the sea and eventually raised above the water; and hence they run so exactly parallel to the shore. Earthquakes, volcanoes, mountain formation, formation of islands and plateaus, the feeble attraction of mountains, and great seismic sea waves,—six great classes of phenomena not heretofore closely associated,—are referred to one common cause, namely, the development of steam beneath the earth's crust, owing principally to the secular leakage of the ocean bottoms. The discovery and verification of this *vera causa* of the principal phenomena of the earth's surface ought to enable us to extend the domain of useful knowledge, and to give a better basis to many of the physical sciences.

Blue Ridge on Loutre,
Montgomery City, Missouri, July 2, 1907.